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THESIS

NPS TINYSCOPE PROGRAM MANAGEMENT

by

Christopher Gordon Turner

September 2010

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13. ABSTRACT (maximum 200 words)

This master's thesis introduces the program management and concept of operations of the TINYSCOPE Program. TINYSCOPE is a 6U CubeSat designed as a low-cost and easily replaceable imaging spacecraft that can produce tactically relevant imagery data. Tactical requirements in this context would emphasize "good enough" image resolution with a rapid-response tasking loop and high revisit rate. The TINYSCOPE project intends to demonstrate the utility of small, risk tolerant spacecraft for tactical imagery.

The program management section of the thesis discusses the relationships of cost, performance, risk, and schedule and the impact of each on the program. The program's successes and failures are examined to glean lessons for future program managers of university projects. The remainder of the thesis develops a comprehensive concept of operations for the prototype spacecraft. Areas of discussion include overviews of the ground, space and launch segments of the mission architecture, and proposed conduct of operations for those segments. Finally, relevant program management and systems engineering documentation are presented as appendices.

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NPS TINYSCOPE PROGRAM MANAGEMENT

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requirements for the degree of

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ABSTRACT

This master's thesis introduces the program management and concept of operations of the TINYSCOPE Program. TINYSCOPE is a 6U CubeSat designed as a low-cost and easily replaceable imaging spacecraft that can produce tactically relevant imagery data. Tactical requirements in this context would emphasize "good enough" image resolution with a rapid-response tasking loop and high revisit rate. The TINYSCOPE project intends to demonstrate the utility of small, risk tolerant spacecraft for tactical imagery.

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

1U	-	Single Unit CubeSat
ADCS	-	Attitude Determination and Control System
APE	-	Activity Planning Element
BER	-	Bit Error Rate
C&DH	-	Command and Data Handling
CARD	-	Certification and Requirements Document
CDR	-	Critical Design Review
CMOS	-	Complementary Metal Oxide Semiconductor
CPT	-	Comprehensive Performance Test
CRC	-	Cyclic Redundancy Check
DME	-	Data Management Element
DoD	-	Department of Defense
EMI	-	Electro-magnetic Interference
EPS	-	Electrical Power System
FOE	-	Flight Operations Element
GPS	-	Global Positioning System
GS	-	Ground Station
GSD	-	Ground Sampling Distance
ISO	-	International Organization for Standardization
ITU	-	International Telecommunication Union
KPP	-	Key Performance Parameter
L&EO	-	Launch and Early Operations
LEO	-	Low Earth Orbit
MOC	-	Mission Operations Center
NACL	-	Nano-satellite Advanced Concepts Laboratory
NEA	-	Non-explosive Actuator
NTIA	-	National Telecommunications and Information Administration
ORS	-	Operationally Responsive Space
P-POD		Poly Pico-satellite Orbital Deployer

SEMP -   Systems Engineering Management Plan

SERB -   Space Experiments Review Board

SMDC -   Space and Missile Defense Command

SOW   -   Statement of Work

STEM -   Science, Technology, Engineering and Mathematics

STP   -   Space Test Program

TCS   -   Thermal Control System

TRL   -   Technology Readiness Level

TT&C -   Telemetry, Tracking, and Command

UAV   -   Unmanned Aerial Vehicle

UTC   -   Universal Time Coordinated

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I would like to acknowledge my thesis advisor and Principal Investigator for the project, Professor Marcello Romano. His mentorship and patience have been the cornerstone of our project's success. I now have a better understanding of what it takes to succeed as a program manager.

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I. INTRODUCTION AND BACKGROUND

A. PURPOSE

This master's thesis discusses the program management and concept of operations of the TINYSCOPE Program. TINYSCOPE is a 6-unit CubeSat designed as a low-cost and easily replaceable imaging spacecraft that can produce tactically relevant imagery data. Tactical requirements in this context would emphasize "good enough" image resolution with a rapid-response tasking loop and high revisit rate. The TINYSCOPE project intends to demonstrate the utility of small, risk tolerant spacecraft for tactical imagery.

The program management section of the thesis will discuss the relationships of cost, performance, risk, and schedule and the impact of each on the program and on the spacecraft design. The remainder of the thesis will develop a comprehensive concept of operations for the prototype spacecraft. Areas of discussion will include overviews of the ground, space and launch segments, and conduct of operations for those segments.

B. EVOLUTION OF OVERHEAD TACTICAL IMAGERY

1. Early Attempts

Information about a potential adversary's actions or intentions provides a significant military advantage to a commander. Thus, it has long been sought after, often in wildly inventive ways. The use of overhead imagery to gain an aerial perspective has evolved from initially fruitless endeavors into a critical component of mission planning and execution at all levels of military operations.

1

The earliest attempts to obtain aerial images were conducted by professional photographers using crude hot-air balloons. Gaspard Felix Tournachon applied for a patent for aerial survey after developing a picture depicting a birds-eye view of Paris in 1858 [1].

The military utility of this new technology was quickly appreciated and the Union Army Balloon Corps was created under the direction of Thaddeus Lowe [2]. At its peak, the Balloon Corps consisted of seven balloons capable of rising to over 1500 meters to allow "aeronauts" to draw maps and report on enemy activities through an on-board telegraph [3].
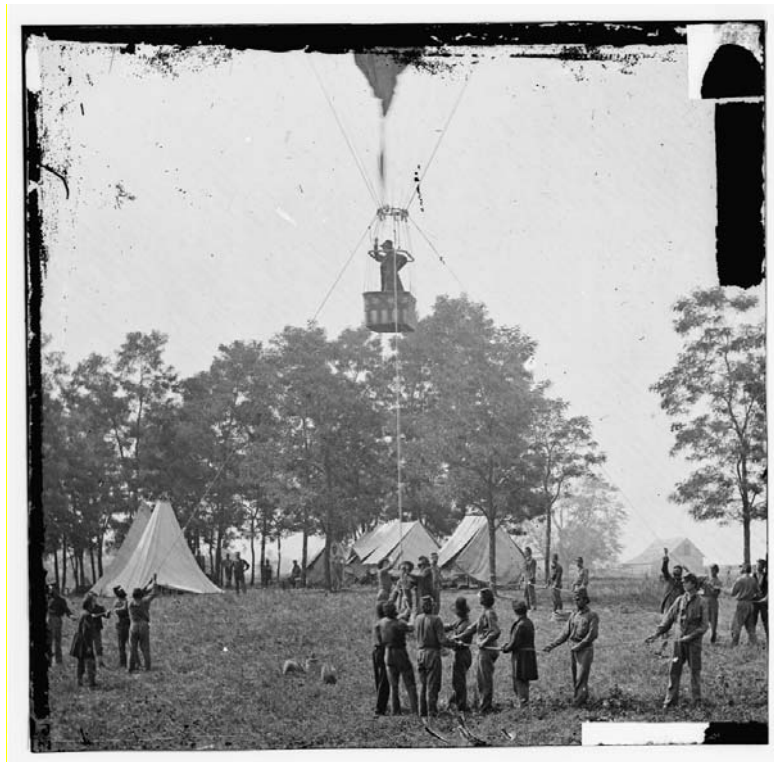
Figure 1. Thaddeus Lowe observing the battle from his balloon the "Intrepid" Fair Oaks, VA 1862. From [4]

Enthusiasm for balloon reconnaissance waned by 1863, perhaps due to the inviting target that a tethered balloon

must have presented. The necessity for reconnaissance did not fade, however, and new techniques were developed that lessened the danger. Arthur Batut, a Frenchman, is known as the father of kite photography. His work, *La photographie aérienne par cerf-volant*, noted the potential for kite photography as a means to provide reconnaissance to militaries. By 1906, George Lawrence, an American, was using strings of kites to take panoramic photos of the devastation caused by the San Francisco earthquake.

Figure 2.   Ruins of San Francisco c.1906. From [5]

Other attempts to satisfy the demand for imagery bordered on the surreal. In 1908, Julius Neubronner was granted a patent for a miniature aerial camera designed to be strapped to a carrier pigeon. The camera and subsequent photographs were a hit at the *Internationale Photographische Ausstellung* in Dresden the following year [6].

Despite the various methods attempted to legitimize the developing field of aerial photography, the discipline did not gain widespread acceptance until the invention of the airplane and the World War that soon followed. Reconnaissance pilots flew countless missions over enemy trench lines to photograph the locations of men, gun emplacements, and materials. By the end of World War II, aerial photography emerged as a critical capability for strategic planners.

2. CORONA

With the advent of the Cold War came the need to determine the strategic capabilities of the Soviet Union. The CORONA program was designed to fulfill that need. The program became the first operational space reconnaissance platform on August 18, 1960. CORONA was a joint program of the Central Intelligence Agency and the United States Air Force. Over the decade long life of the program, CORONA gathered photographic images of more than 600 million square nautical miles of the earth. Images ranged in resolution from 25 feet at the beginning of the program to six feet as the program drew to a halt. The CORONA program is frequently showcased as an example of how a technology can revolutionize an industry [7].
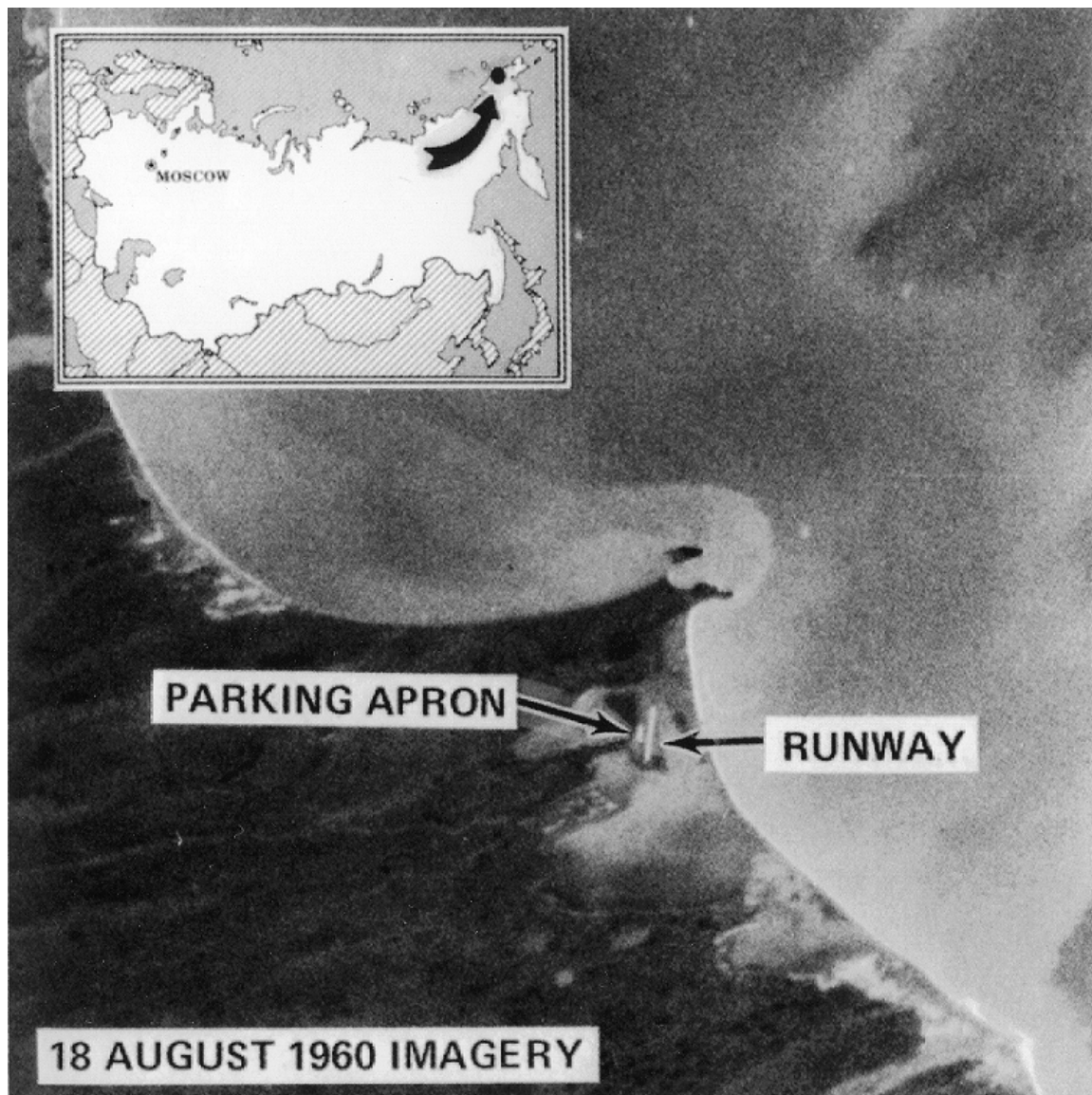
Figure 3.   First imagery recovered from CORONA, Mys Shmidta
         Air Field, USSR.   From National Reconnaissance Office.

3.   Current Technology

Satellite technology has continued to evolve since CORONA.   Current commercial satellites are capable of producing images of nearly a million square kilometers per day.   Options include multispectral images or panchromatic shots at resolutions of less than one-half meter.   National

imagery collection systems are undoubtedly capable of the same feats. Unfortunately, while technology has allowed us to take more and better pictures, physics still dictates that a single satellite is unlikely to be able to photograph the same location on earth more than a few times per day.

C.   TINYSCOPE PROGRAM

1.   Background

Strategic intelligence has traditionally been the focus of imagery collection, particularly space-based collection. However, as threats have evolved from peer competitor states to more regional, imagery requirements have adapted as well. Operations DESERT SHIELD and STORM witnessed a shift to operational ISR to allow theater campaign planning. The trend continued toward lower echelon use of national imagery systems throughout the intervening period prior to the World Trade Center bombing in 2001 [8].

Entry into Operations IRAQI FREEDOM and ENDURING FREEDOM further shifted the use of overhead imagery into the tactical realm. The use of Unmanned Aerial Vehicles (UAVs) has become ubiquitous even at the platoon level. Along with the UAVs has come a reliance on the availability of real-time imagery, and thus, a demand for responsiveness that national systems cannot meet.

Blocker's suggested solution is a constellation of imaging nano-satellites that would provide near real-time imaging capability to the warfighter [8]. The TINYSCOPE Program is an attempt to design, build, and fly a prototype

nano-satellite similar to the one that Blocker envisioned. The project seeks to use the CubeSat standard and commercial off-the-shelf hardware as much as possible to develop a low cost flight unit for flight testing and concept validation.

2.   CubeSat Standard

CubeSat is a pico-satellite design standard that was developed by California Polytechnic State University and Stanford University in 1999. The standard defines size and mass restrictions, as well as interfaces with the deployment system. A standard single unit (1U) CubeSat is a 10cm cube and has a mass of 1.33kg.
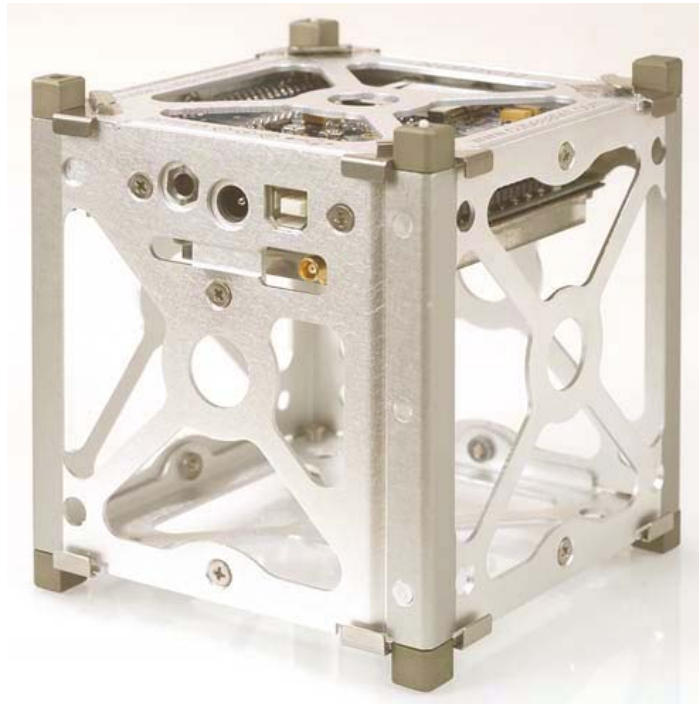
Figure 4.   1U CubeSat

CubeSats are commonly expanded into a 3U form factor measuring 10cm X 10cm X 30cm [9]. Both form factors are typically launched using a standardized CubeSat deployment

system, such as the Poly Picosatellite Orbital Deployer (P-POD). "The P-POD is an aluminum box with a door and spring mechanism that can accommodate up to three 1U CubeSats or a single 3U CubeSat. Upon receipt of a deployment signal from the launch vehicle, a non-explosive actuator (NEA) releases the door and allows the CubeSats to slide along a series of rails and eject from the P-POD [10]." The CubeSat design standard does not currently allow for alternative form factors based on the standard, however, a 6U design is in development by NASA Ames.

3. Program Objectives

The TINYSCOPE project intends to demonstrate the utility of small, risk tolerant spacecraft for this purpose. The objectives of the TINYSCOPE mission are stated below.

a. The primary objective of the TINYSCOPE program is facilitation of student education at the Naval Postgraduate School.

b. The second critical objective is to launch and operate one TINYSCOPE spacecraft capable of obtaining a single image of a newly tasked target along a predetermined low earth orbit and transmit image to a known stationary ground station.

c. Another objective is to develop an attitude determination and control system to provide accurate and agile pointing for nano-satellites.

d. Finally, it is desired to exploit advantages of CubeSat platforms. This objective will require the project to include small subsystems requiring minimal power, mass, volume, and cost to operate.

II. TINYSCOPE PROJECT MANAGEMENT

A. SYSTEM DEVELOPMENT PLANNING

Project Management may be represented as a discipline composed of two constituent parts: Systems Engineering and Project Planning and Control. Figure 5 depicts the activities, which together comprise the project management domain [11]. In reality, the individual provinces may be considerably less distinct. In our case, the TINYSCOPE team does not have a dedicated systems engineer. Many of the tasks that would traditionally be performed by a dedicated systems engineer were instead added to the program manager's responsibilities.
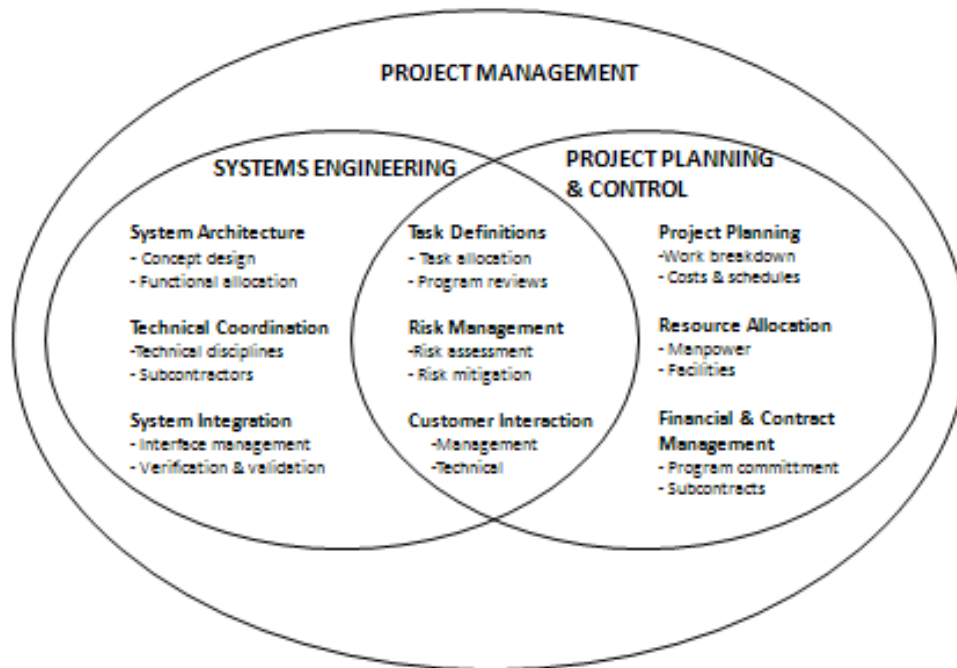
Figure 5.   Systems engineering as a part of project management After [11]

1. Feasibility Assessment

One of the first steps in the design of any new system is the analysis of feasibility. In the case of the TINYSCOPE program, this assessment was performed by Blocker and Litton [12]. Blocker broadly outlined the subsystems that would be required to develop a spacecraft bus, while Litton focused on the optical imaging payload. The two efforts were complementary; each defined required functions and interfaces for their respective components. Together they developed an initial system definition, top level requirements for the system, and showed that their proposed system was feasible given current technologies.

Blocker defined the TINYSCOPE system to be a three-axis stabilized, low earth orbit satellite with an electro-optical payload. The attitude determination and control system (ADCS) would be used for stabilization and pointing. Attitude and location determination would be provided by onboard sun sensors and star trackers. Attitude control would be performed by either reaction wheels or control moment gyroscopes. Imaging would be conducted on command from a ground station accessible by direct line of sight. The satellite would use a series of slew maneuvers to point to the targets and then point back at a ground station and transmit the images via a radio downlink. Power requirements for the satellite would be met using body mounted solar panels and batteries [8]. Litton described the payload as an axially mounted Cassegrain telescope with an on orbit focusing mechanism. Images would be captured using a COTS focal plane array, like those used in digital cameras [12].

Blocker and Litton used the above system definition and the broad guidelines outlined by the Operationally Responsive Space Office (ORS) to develop a set of top level requirements for TINYSCOPE. These initial requirements shown in Table 1, served as the foundation for the TINYSCOPE program.

Summary of TINYSCOPE and Argus Requirements

	Requirement	Threshold	Objective	
Mission	IOC	Sep 2011	ASAP	*note 1*
	MMD ~yrs	1	2	*note 2*
	Storage Life	2	3	
	Reliability confidence	80%	80%	
	Revisit ~hrs	1	0.5	*note 3*
	Images ~per day	30	60	
	Task-to-collect ~hrs	4	1.75	*note 4*
	Task-to-product ~hrs	4	2	*note 4*
	Data Storage ~orbits	2	3	
	Orbit	Sun-Synch	45 to Sun-Synch	
Imager	footprint ~km^2	25	50	
	Max Slew Angle	30	45	
	NIIRS	3	4	
	Spacial Resolution ~m	4	2.5	
TT&C	Operations	MMSOC, AFSCN		
	Imagery Downlink	CDL, DCGS		

Notes: 1. Initial Operational Capability
2. Mean Mission Duration
3. Revisit requirement for Argus constellation, not individual satellite.
4. Based on Mission Planning timelines. Allows tasking of satellite at beginning of final mission plans with product in time for brief

Table 1.   Initial TINYSCOPE Top-Level Requirements
From [8]

2.   Early Management Efforts

An important early step in the development of a system is a description of the scope of the project. A statement of work (SOW) is typically used to document broad responsibilities, deliverables, and the work activities required in a given project. The SOW acts as a guideline

for the project and in some cases is a binding contract between the vendor and the customer. The TINYSCOPE program, like many university projects, does not have a defined customer. Instead, proposals for funding that were submitted to sponsoring agencies became the de facto SOW. Due to the annual nature of these funding proposals, the work defined in each is limited in scope to what is to be performed in the funded year. The changes in scope each year inevitably have an impact on cost and schedule, but seem to be a byproduct of the lack of stable, long-term funding from the sponsors and may also be an inherent part of the learning process for any team attempting to build a satellite for the first time. Continuity was maintained through focused meetings and a positive working relationship between the students on our team and our faculty advisers.

Concurrent with the feasibility analysis being conducted by Blocker and Litton in 2007, TINYSCOPE was being explored as a student research development project by Dr. Marcello Romano. Initial proposals for funding were limited in scope to numerical simulations and preliminary hardware testing for the TINYSCOPE attitude control and optical systems. Deliverables were equally limited; they included attitude control algorithms, test data for COTS optical components and a prototype micro-CMG. Shortly after the initial research proposal, the scope of the TINYSCOPE program was greatly increased. By the end of 2008, there were ideas to design, build and launch a prototype TINYSCOPE spacecraft. An engineering design unit was scheduled to be complete and functional by the end of 2009. The proposed flight prototype was scheduled to be ready for

launch by the end of 2011. Efforts began immediately to find suitable COTS components and where necessary to design and test custom hardware subsystems.

The compressed timeline and the lack of a dedicated systems engineer forced much of the documentation that would be expected in a project following accepted systems engineering practices to be curtailed. An exacerbating factor was the lack of a standard format for systems documentation. As a result, the three fundamental priorities of project management, cost, performance, and schedule, were often difficult to ascertain or finalize, but this, too, is not unexpected for an inexperienced student team working its way through the complexities of such a project. Capturing as much as possible of what is learned each student cycle enables the next cycle to build on the experiences of the last.

Cost estimation is tricky for even an experienced budget analyst and it should not have been surprising that initial estimates for the TINYSCOPE program were optimistic. Blocker's feasibility assessment estimated the cost for a TINYSCOPE satellite to be approximately $250k [8]. This number was used as the baseline cost estimate for the program. We failed to appreciate that Blocker's estimate was intended to be a life-cycle cost of an individual satellite in a constellation of 360 satellites. In that case, development and operational costs were to be spread over the entire constellation. Our TINYSCOPE prototype would require the same development costs for a single satellite, ballooning estimates by an order of magnitude.

Early attempts to define requirements were vague and incomplete. The top-level requirements shown in Table 1 along with a minimal set of derived requirements gleaned from Blocker's feasibility assessment and shown in Table 2 served as the program's only requirements documentation well into the preliminary design phase. The requirements that did exist were poorly written and open to misinterpretation. As a simple example, a top level requirement in Table 1 called for the Task-to-product time to be within four hours with an objective of two hours. This requirement may be interpreted as the time between when a Soldier submits a request for an image to the time an image is available to that Soldier. Alternatively, it may be interpreted as the time between the tasking of the satellite by a ground station and the time an image is transmitted back to the ground station. In practice, this vagueness made it very difficult for the student engineers to design or select subsystems.

Top Level to Subsystem Requirements

- EPS (**INITIAL** power budget)
  - Subsystems will be mainte around 4 Watts max (Comms, Payload, EPS, C&DH / TT&C)
  - MED suite including sensors by exception (ADCS, Sun, Star, IMU, Mag, GPS)
  - Clyde Space PCU
- Structure
  - Capability to launch via P-Pod (Cal-Poly Requirements)
    - 6U : Utilizing primarily COTS infrastructure (exception payload & MED suite)
    - 5U : Utilizing custom parts
  - Payload volume restricted to 10 x 10 x 33 cm at launch
  - Initial mass budget total 10 kg
    - 3.5 kg Payload
    - 1 kg EPS inc solar arrays
    - 1.5 kg ADCS inc sensor
    - 1.5 kg Structure
    - 1 kg Comms
    - 1 kg C&DH & TT&C
    - .5 kg Cabling and Connections
- C&DH : floating point processor......
- Comms : Payload and command data, transmit receive.........
- ADCS : .81 deg / sec +/-.18 ....
- Payload : Given 1 ms exposure, provide 3m GRD......

Figure 6.   Derived requirements for TINYSCOPE following internal Mission Requirements Review

The initial schedule for TINYSCOPE, shown in Figure 7, was far too aggressive for a student-led project of this scope.   Optimistic assessments like this were common when the project began due to the inexperience of the team. Often we failed to fully grasp the difficulty of our undertaking and the environment in which we worked.

Task Name	Start	Finish
Create Spacecraft (S/C) Design 1, Tinyscope 1	Mon 10/27/08	Fri 9/4/09
Concept Architecture / Development	Mon 10/27/08	Wed 11/26/08
S/C DESIGN 1 SYSTEM FUNCTIONAL REVIEW (Internal)	Fri 11/14/08	Fri 11/14/08
CRITICAL DESIGN DOCUMENTS (ALCH Thesis')	Fri 12/19/08	Fri 12/19/08
'NEW' MISSION REQUIREMENTS REVIEW	Thu 3/12/09	Thu 3/12/09
PRELIMINARY DESIGN REVIEW (Informal w/SSAG)	Tue 3/31/09	Wed 7/8/09
Develop S/C design (by subsystem)	Mon 10/27/08	Mon 3/30/09
Detailed/Final Subsystem Design	Mon 1/12/09	Fri 4/17/09
TINYSCOPE S/C CRITICAL DESIGN REVIEW	Fri 4/17/09	Fri 4/17/09
Tinyscope Common Ground Support Equipment (GSE) Feasibility Researc	Mon 1/12/09	Mon 5/18/09
Build Structural / MED Test Vehicles (STV) and Simulators	Mon 1/12/09	Tue 5/26/09
TINYSCOPE S/C IN PROGRESS REVIEW	Fri 5/29/09	Fri 5/29/09
Build S/C subsystems	Mon 3/23/09	Fri 7/24/09
Qual/Test S/C subsystems (as independently as possible)	Mon 3/23/09	Fri 7/24/09
TINYSCOPE S/C IN PROGRESS REVIEW	Mon 7/6/09	Mon 7/6/09
Integrate Tinyscope Design 1 (EDU)	Mon 6/1/09	Fri 8/14/09
Qualify/Test Tinyscope Design 1 (EDU)	Mon 8/3/09	Fri 8/28/09
SYSTEM VERIFICATION REVIEW / PRODUCTION READINESS REVIEW	Fri 9/4/09	Fri 9/4/09

Figure 7.   Initial TINYSCOPE Project Schedule 10 February 2009

With the advantage of hindsight, it is clear that the TINYSCOPE program had many program difficulties from the outset. Most of these shortcomings can be attributed to a lack of experience and a failure to understand the importance of the systems engineering process in the development of a system. Some of the program's shortcomings might have been averted with a rigorous documentation process. Other difficulties were created or impacted by the university environment. Many of these impacts will be explored further in the following section including the nature of our work force, infrastructure, and funding.

Despite its challenges and program difficulties, the TINYSCOPE project has proven to be a tremendous learning experience. The author has gained valuable experience as a program manager in an environment where mistakes were tolerated and treated as an educational opportunity. Many of the difficulties that have been examined in this chapter

may have been preventable, but that is often the nature of education. In any event, the lessons have been learned and will be documented here.

B.   PROGRAM MANAGEMENT CHALLENGES

1.   Student Work Force

A significant reality of any university program is the student work force. There are both advantages and disadvantages to the use of student labor for a satellite program, but it requires planning and continued management to optimize the tradeoffs. The primary advantage to student labor is the knowledge and experience gained by the student. Disadvantages of student labor include inexperience, frequent turnover, and limited availability. However, with proper management these disadvantages can be overcome or at least minimized.

The chief objective of the TINYSCOPE program is to facilitate the education of the university's student population. Due to this, it made practical sense that student's would perform the majority of the tasks associated with the design, management, and construction of the satellite. On the TINYSCOPE team, individual students were responsible for the design, testing, and construction of individual subsystems of the satellite. Additionally, the team had a student responsible for integration of the subsystems and a student program manager. Frequent interaction between our team ensured that each participant gained understanding of a good portion of the breadth of satellite design.

The members of the TINYSCOPE team come from varied
military and civilian backgrounds, but the overwhelming
majority had not had prior experience in the space
industry. Instead the required knowledge and experience is
gained from the curriculum, through self-study, through on
the job training, through hand-overs with previous
students, and finally through interacting with permanent
support engineers. Gaps sometimes occur when students join
the development team before they have gained the requisite
knowledge. A key to overcoming these situations is to
understand the institutional knowledge and experience that
is available from professors, staff engineers, and support
staff at the university and collaborating agencies. One of
the most important lessons the author gleaned from this
experience was to enlist the help and support of those
persons early in the planning process. It may be helpful
to identify the types of knowledge or support that will be
required during the systems definition process and then
list those who may be resources in planning documentation.
Those persons should then be encouraged to attend some or
all of the team's development meetings to provide their
perspective and insight. Formalizing the relationship
between the design team and external staff resources
through documentation will help to capture any costs that
may be associated with their involvement. It will also
provide a starting point for new members of the team to
seek assistance.

Another possible drawback to using student labor is
their high turnover rate. Members of our team average
approximately one year on the team before graduating. Each
time a member leaves there is a risk that not only his

experience will be lost, but also that any knowledge developed will disappear as well. Managing transitions to ensure that a member's contributions are documented and that responsibilities are assumed by another member of the team is a significant challenge. It only took our team a single mishandled transition to realize the importance of having a standard procedure for outgoing personnel to follow. Ideally this procedure would be outlined in the program's Project Management Plan.

A final vital lesson that the author learned in regard to student labor is to never assume availability. Students join a satellite development team to be a part of something interesting that will have a lasting impact. At our university it is a voluntary act. Students will always have conflicts between classes, other projects, and non-school activities that will limit the time available for the project. There will also be periods of time when recruitment of students becomes difficult, causing the project to stall. At one point in the TINYSCOPE development, we had five engineers one month and one the next. It is important to account for this factor when establishing development timelines and work and meeting schedules. Development timelines that are merely aggressive in industry become unrealistic in a student environment. One approach to resolve this dilemma, proposed for the first time in this thesis since the beginning of the TINYSCOPE project, is to establish task oriented metrics for measuring progress rather than a simple GANNT chart depicting start/stop dates.

2. Infrastructure

Special facilities are typically required in order to conduct integration and testing of space systems [11]. These may include facilities for environmental and qualification testing, environmentally controlled areas for testing and integration, or specialized test-beds for subsystem testing. For the TINYSCOPE program, our team determined early on that we would require a contamination controlled environment for subsystem testing and integration, as well as final assembly. We also realized that we would require specialized equipment to test our attitude control system and optical payload. Environmental and qualification testing would be performed using facilities available at the university. To minimize our production timeline, we decided to develop or purchase the required test and integration facilities in parallel with design and development of the system.

The contamination control procedures for the TINYSCOPE program are based on the sensitivities of the on-board instrumentation and risk tolerances for the program as defined in the Project Plan in Appendix A and the Contamination Control Plan in Appendix C. Generally, integration and assembly of the spacecraft subsystems will be accomplished in International Organization for Standardization (ISO) Class 6 clean rooms. Our university had two such facilities; however, both facilities were in use by other projects during the TINYSCOPE planning phase. Our team determined that it was necessary to build our own facility in the Nano-satellite Advanced Concepts Lab

(NACL). Our facility was completed at relatively low cost using commercially available equipment.

A new three-axis attitude dynamics, navigation, and control hardware simulator will be used to test the hardware and the software components of the attitude control and determination system. The simulator consists of a pedestal supporting a hemispherical cup in which the ADCS system will be free floating using a hemispherical air bearing. The air bearing will allow the simulation of a zero gravity environment.

Development of an optical payload test bed had not begun at the time this thesis was written. There are, however, several requirements that such a test bed must meet. The test bed must be able to determine the accuracy of the telescope's alignment with the focal array. This can be done in a variety of ways, most commonly through the use of an interferometer. The test bed should allow determination of the payload to provide contrast. Ideally, the test bed would help to define the modulation transfer function of the telescope as well. The test bed should allow both the payload by itself and the entire system to be mounted and tested in a thermal environment similar to expected orbital values. Finally, the test bed should allow measurement of distortion caused by vibration of the spacecraft's attitude control system.

3.   Funding

To effectively manage a project it is important to correctly forecast both direct and indirect costs throughout the project lifecycle. For the TINYSCOPE project, the primary investigator chose to maintain control

of budgetary decisions to preserve fiscal partitions between separate but complementary research areas. These included the parallel development of test facilities and a separately funded nano-satellite attitude control system.

As the student program manager, this limitation in budgetary authority had benefits. The amount of time and effort that was required for day-to-day management tasks, such as developing purchase orders was greatly reduced. Additionally, because the program manager did not have visibility of travel, labor, or indirect costs associated with the project, budgetary estimates were easily developed based on hardware costs only.

However, there were also inherent disadvantages to this budgeting scheme. The experience and knowledge missed by not working through the complexities of the university's accounting and contracting process are vital to understanding project management. Ownership of the project budget also forces the manager to balance the relationships between cost, schedule, and performance to a greater degree. In principle, monetary or labor assets may be allocated to one subsystem that is behind schedule in order to bring the project back into compliance with the schedule. Choices between components that have marginally different performance or risk become much more meaningful and are likely to be more considered when the decision maker is responsible for the money being spent.

4.   Outreach

One of the unique and most enjoyable aspects of being a student program manager is the opportunity to engage with other organizations, institutions, and individuals pursuing

complementary ideas. Typical engagements may be broadly categorized as marketing, collaborative, or requests for services.

Marketing engagements are an opportunity for our team to generate interest for the project from our eventual customers, the warfighter. They are also used to gain feedback from the personnel who will ultimately use the imagery provided by the TINYSCOPE satellite. It is common for the student program manager to provide marketing presentations to service commands such as the Army's Space and Missile Defense Command (SMDC) and to representatives of the Intelligence Community.

Collaborative engagements are conducted to share ideas and foster relationships with other academic, civil or commercial entities that work in the small satellite community. Meetings may be conducted formally or informally with a single or multiple organizations. Our team considered the annual CubeSat Developer's Workshop hosted by California Polytechnic State University to be an excellent forum for the exchange of ideas and perspectives.

Requests for services may be for funding, technical assistance or launch and integration services. The TINYSCOPE program relies on funding from external government agencies to operate. The funding cycle is annual and does not usually allow fiscal assets to be carried over from year to year. This necessitates annual proposals to request additional research funding for the project. It also requires that periodic progress briefs are presented to sponsoring agencies. Launch services for scientific or experimental Department of Defense (DoD)

satellites are provided through the Space Test Program (STP). The STP manifests experiments which either enhance or provide new capabilities to the DoD and that have been approved by the Space Experiments Review Board (SERB). The TINYSCOPE project has received annual approval as an eligible experiment since 2008.

C.   SYSTEMS ENGINEERING EVOLUTION

There is a complex interrelationship between cost, performance, schedule, and risk that must be balanced effectively in a systems development program. Cost and schedule are directly linked; similarly, cost has direct linkage to performance and risk. As an example of these relationships assume that schedule and risk remain constant while performance requirements increase; the cost of the program will likely increase. Performance, schedule and risk are all indirectly linked to each other through cost. The function of managing the relationships between these elements is the responsibility of the project manager. The key to success is appropriate planning and documentation. As I have already described, the TINYSCOPE program suffered from a lack of planning and documentation from its inception. This was apparent almost immediately after volunteering to be the program manager. Our team attempted several stopgap measures to keep the program on track but our inexperience was palpable. Figure 8 is an early attempt to manage our requirements gap. We developed key performance parameters with objective and threshold values to define the capabilities we expected of our system.

KPP	Description	Objective	Threshold	Units
001	Mission life (Design Life)	2	5	yrs
002	Reliability	80	50	%
003	Earth imaging resolution (sensor)	1*	5	m
003.a	Assuming orbit altitude	450-550	400-600**	km
003.b	Orbit inclination	60-98	sun synch	deg
003.c	Effective field of view	50	25	km^2
004	Satellite Mass	10	20	kg
004.a	Deploy from available design	P-POD	NASA	m^3
006	Downlink tactically usable imagery	4	1	images
006.a	Telemetry and Command up-link / down-link	ITGT and or other SAT	NPS**	
006.b	Payload Data down-link	ITGT and or other SAT	NPS**	
006.c	Ground station antenna size	3	10	m
007	Tactical Slew Maneuver: Serviced Users / Target assignment			
007.a	Number of targets during pass	5***	2**	targets
007.b	Angle between target	60	30	deg (angle)
0007.c	Latitude bounds	10	5	deg (latitude)
008	Cost	500K	1M	$
009	Geo Location	100	200	m
010	Storage Capability	36	12	images

Note * - estimated capability orbit dependent: desired mission altitude vs mission life

Note ** - assumed precedence during prototype increment

Note *** -includes ground station acquisition and 4 target areas

Figure 8.   TINYSCOPE Key Performance Parameters July 2009.

Development delays and frequent miscommunication among team members about responsibilities and interfaces remained prevalent.   As development continued, the author again realized that these measures were not enough, so in 2010, we began a systematic overhaul of the program beginning with a project plan, a reconstructed requirements document and a task oriented schedule.

The TINYSCOPE project plan in Appendix A describes the work activities required to develop a flight prototype.   It acts as the defining document for the program's mission and objectives and describes the technical approach that will be used by the development team.   It additionally defines criteria for minimum and complete success of the system upon launch.   The document outlines the team's management and product structure and provides a baseline schedule and budget estimation for the program.   The project plan acts as a foundation document for all other TINYSCOPE documentation.

The Certification and Requirements Document in Appendix B describes all of the system's bus, payload, mission and technology, and master satellite interface requirements. It additionally defines required tests and inspections for the system and describes the methods and analysis procedures for the test and certification program.

III. TINYSCOPE CONCEPT OF OPERATIONS

A. MISSION ARCHITECTURE

1. Space Environment

TINYSCOPE will conduct normal operations in a low earth orbit. The nominal orbit is sun-synchronous and circular at an altitude of 400 kilometers. The natural environment at this orbit includes the gravitational fields, plasma, magnetic fields, energetic charged particles, galactic cosmic rays, and meteoroids. An additional concern is manmade orbital debris.

a. Perturbations

The Earth-Moon system will perturb the TINYSCOPE spacecraft's orbit due to eccentricity of the Earth-Moon orbit and the rotation of the Earth and Moon. The planets will also perturb the orbits with Jupiter and Venus acting as the primary sources. Additional sources of perturbation include solar radiation pressure and atmospheric drag. These perturbations will vary due to attitude changes of the spacecraft.

b. Plasma

A spacecraft in a Low Earth orbit is subject to plasma environments due to both the solar wind and the geomagnetic tail. TINYSCOPE will operate within this extremely dynamic plasma environment risking damage from spacecraft charging, contamination, and interference with communication and other electronic hardware due to scintillation and wave refraction. Typical charged

particles will have energies of a few hundred kilovolts. Differential collection of charge on the external surfaces of the spacecraft may lead to electrostatic discharge events and attraction of contaminants. Severe charging can also interfere with electronic systems.

orbit	space hazard / specific cause	spacecraft charging: surface	internal	single event effects galactic cosmic rays	trapped radia-tion	solar particle	total radiation dose trapped radia-tion	solar particle	surface degradation ion sputter-ing	O+ erosion	plasma interference with spacecraft communication scintilla-tion	wave refract-ion
	LEO i<60	1	1	not applic-able	2	not applic-able	2	1	1	2	2	2
	LEO i>60	1	1	2	2	2	2	1	1	2	2	2
	MEO	2	2	2	2	2	2	2	1	2	2	2
	GPS i~55	2	2	2	not applic-able	2	2	2	1	2	2	2
	GTO	2	2	2	2	2	2	2	1	1	2	2
	GEO	2	2	2	not applic-able	2	2	2	1	1	2	2
	HEO	2	2	2	2	2	2	2	1	1	2	2
	Inter-planet-ary	not applic-able	not applic-able	2	not applic-able	2	not applic-able	2	1	not applic-able	1	1

Table key:
2 important
1 relevant

Table 2.   Space Environment Hazards by Orbit From [13]

c.   Energetic Particles

TINYSCOPE will be subject to the effects of energetic particles, or ionizing radiation, produced by solar flares and coronal mass ejections, the geomagnetic tail, and galactic cosmic rays. The spacecraft will also encounter ionizing radiation trapped in the Van Allen belts and in particular the South Atlantic Anomaly. This ionizing radiation can cause several types of damage. These effects include measurable changes in properties of

semiconductors and a deterioration of the thermal radiation properties of materials due to the cumulative penetration of the particles. The energetic particles can also cause single event upsets to microcontrollers and changes in the surface reflectivity and transmission properties of optical sensors. Energetic particles will also add noise to images due to direct impacts with the sensor. This effect will be measurably more pronounced during periods of high solar activity.

d. Surface Degradation Hazards

Low Earth orbital atomic oxygen is highly reactive and erodes the external surfaces of surface materials. Atomic oxygen is very damaging to surface optical properties while some coatings, such as silver and osmium, are seriously degraded resulting in material removal or surface roughness. UV degradation may occur as well due to the presence of ultraviolet and X-ray wavelengths. It is expected that some amount of sputtering will occur but it is unlikely to limit operation of the spacecraft.

e. Orbital Debris and Meteoroids

Orbital debris will be a major concern for the spacecraft. There are currently over 20,000 catalogued objects greater than five centimeters in diameter in the low earth orbit environment. Kinetic impacts with debris objects could potentially be fatal to the spacecraft. Expected mass of meteoroids will be between .001 and 1 gram.

2. Space Segment Overview

a. *Payload*

The TINYSCOPE payload consists of an optical telescope and a focal plane array. The telescope is a Matsukov-Cassegrain design with a spherical primary mirror and a slightly aspherical secondary mirror mounted near the focus of the primary mirror, as depicted in Figure 9. The secondary mirror includes a smaller meniscus corrector in the center that reduces off-axis aberration and narrows the field of view. The effective focal length of the telescope is 1.45 meters. The diameters of the primary and secondary mirrors are each 9.3 centimeters. The mirrors will be aligned and focused on the ground and do not have an onboard focusing mechanism.
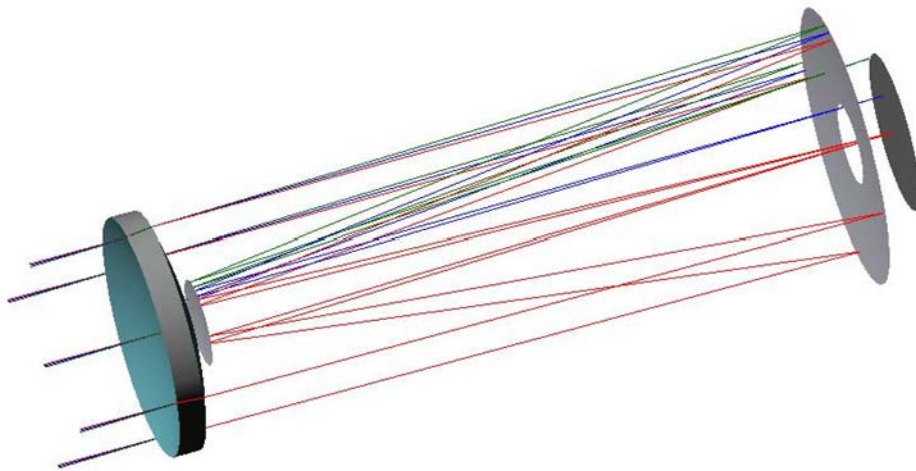

Figure 9.   Light path of a Matsukov-Cassegrain telescope.

The focal plane array consists of a 4.8 centimeter monochrome Complementary Metal Oxide Semiconductor (CMOS) housed in a Toshiba_Teli, machine vision camera housing. The planar array is 4096 pixels by

3072 pixels and each pixel is 6.0 micrometers square. Each pixel has a dynamic range of up to ten bits. The camera has an electronic shutter and is capable of capturing 25 frames per second at full resolution.

b.   *Spacecraft Bus*

The TINYSCOPE bus provides power to the focal plane array, attitude control, command and data handling and communications. The bus is constrained to be a 6U CubeSat form factor and subsystems are limited to one half of the overall volume as shown in Figure 10.
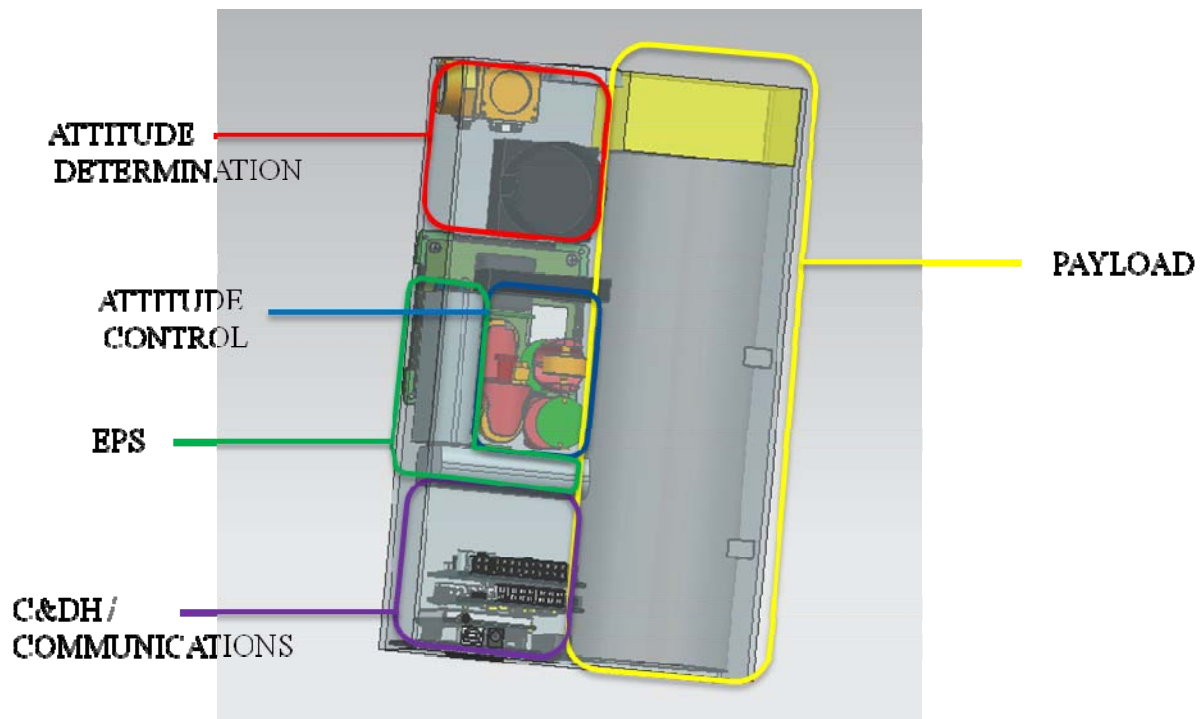

Figure 10.   TINYSCOPE Volume Configuration

(1) Electrical Power Subsystem (EPS). The EPS consists of the power controller, the solar arrays and the batteries. The power controller provides regulated power to the payload and bus subsystems. It conditions the power generated by the solar arrays, provides circuit

protection, and monitors the battery state of charge. The solar arrays will use GaAs solar cells to power the spacecraft. The battery will provide initial power to the spacecraft following launch and will provide power during normal operations when the spacecraft is not sun soaking.

(2) Attitude Determination and Control Subsystem (ADCS). The ADCS will provide location and attitude knowledge, momentum management and pointing control to support normal operations. Attitude and location determination will be provided by a combination of sun sensors, a star tracker, an inertial measurement unit and an on-board Global Positioning System (GPS) receiver. Pointing control will be performed by reaction wheels. The ADCS will control spacecraft slew maneuvers in response to commands from the ground station and to return the spacecraft to a sun soaking attitude. Magneto-torquer coils will be used to dump momentum when the reaction wheels become saturated or in response to commands from the ground station.

(3) Thermal Control Subsystem (TCS). The TCS will be a passive radiation system. The spacecraft structure will act as a heat sink to collect thermal energy from subsystems. Heat will be radiated through flat-plate body mounted radiators.

Command and Data Handling Subsystem (C&DH). The C&DH subsystem consists of the command and data processor, solid state data storage, and the cabling that provides connectivity to the other spacecraft subsystems. The command and data processor controls the spacecraft subsystems and manages the spacecraft state of health. The processor will compress collected images and segment the

data for transmission to the ground station. The data storage is used to store collected images and state of health logs between contacts with the ground station.

Communications Subsystem. The communications subsystem provides two way communications for command uplink and telemetry and data downlink. The S-Band radio will operate at 2.4 GHz and will provide a data rate of 1.2 Mbps through a directional antenna. A secondary omni-directional antenna will provide low rate communications for telemetry and commands during contingency operations.

3. Ground Segment Overview

The TINYSCOPE ground segment includes the Mission Operations Center, the ground station and associated networks. The Mission Operations Center (MOC) is responsible for flight operations, activity planning and data management. The ground station acts as the communications element of the ground segment. The ground station is required to provide daily contact with the spacecraft to allow telemetry and data downlink and command uplink. Ground segment networks include the link between the ground station and the Mission Operations Center, the Naval Postgraduate School Intranet, and the internet.

a. Mission Operations Center

The Mission Operations Center consists of three operational elements: flight operations, activity planning and data management. The flight operations element communicates with and controls the satellite through the ground station. Activity planning and data management

33

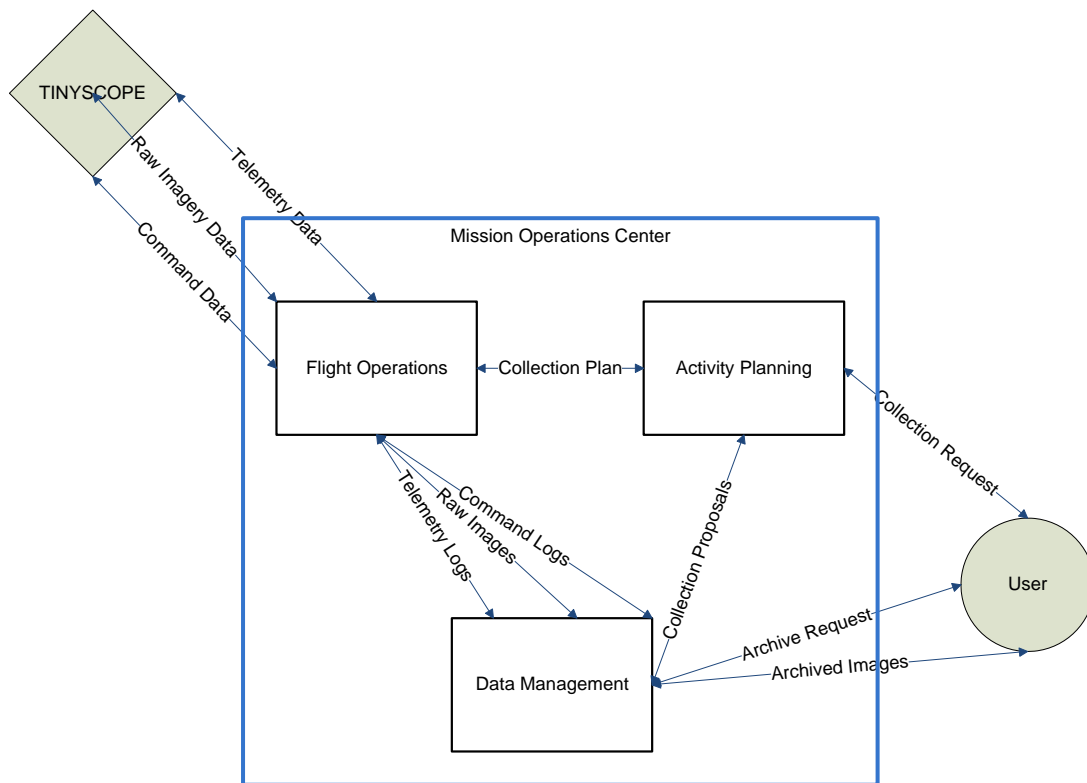interact with the end user of the TINYSCOPE product. Figure 11 shows how each element interacts with others.

Figure 11.   Mission Operations Center elements

b.   *Ground Station*

The TINYSCOPE ground station will provide an intermittent link between the satellite and the flight operations element. Currently, we plan to utilize the ground station on the Naval Postgraduate School campus that was built for another NPS satellite project, the NPSAT1 [14]. The ground station consists of a steerable antenna, a telemetry tracking receiver, high and low frequency synthesizers and computer hardware with orbit propagation software. A diagram of the architecture is in Figure 12.
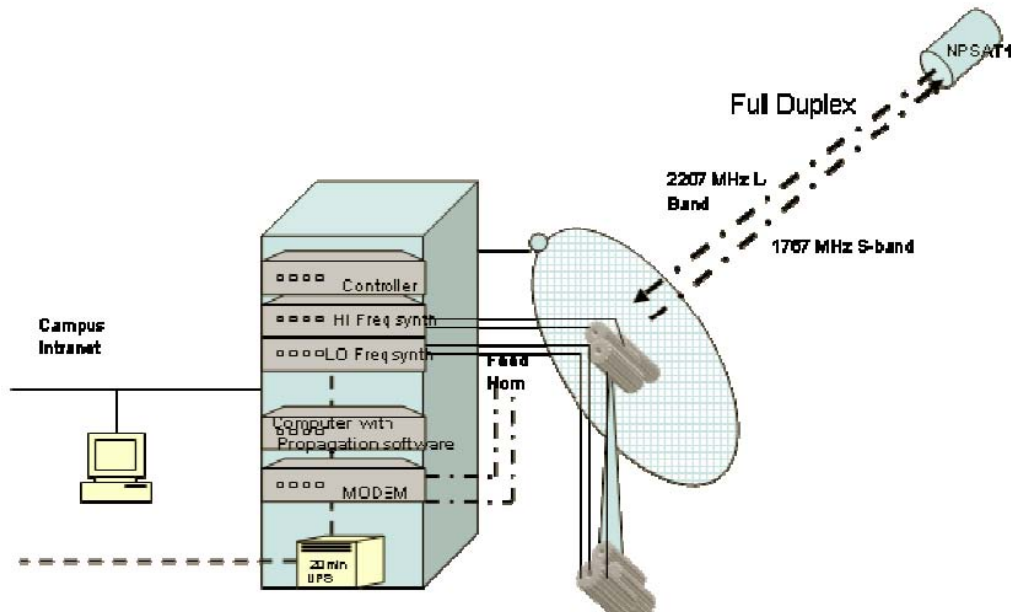
Figure 12.   Ground Station Communications Architecture From
[14]

The steerable antenna is a 3.048 meter in diameter mesh parabolic dish. The antenna's beamwidth is between three and four degrees. The pointing accuracy is approximately two and one half degrees. The antenna has a maximum elevation of 90 degrees and azimuth limitations of 374 degrees, which will create a keyhole effect as a satellite passes overhead, reducing contact times with flight operations [14].

The antenna steering is controlled by the telemetry tracking receiver, which locks onto the signal from the satellite. The receiver sends commands to a controller box, which then engages azimuth and elevation motors to move the antenna. The orbit propagation software predicts the satellite's orbital position based on previous ephemeris to provide the antenna controller with an initial search position.

35

c. *Ground Segment Networks*

The ground segment networks provide physical links between the mission operations center and the ground station and allow end users to gain access to archived images. The campus intranet will be used for the former purpose using existing cabling. Archived images will be placed in a database by the data management element and will be available via a web interface.

B. OPERATIONS DESCRIPTION

1. Spacecraft Operations

The TINYSCOPE satellite points to, and takes panchromatic images of, specified locations on the earth and transmits the images to a ground station. Generally, the satellite will receive a command from a ground station to image one or more locations. The satellite will then calculate the necessary slew maneuvers to point to the specific locations, conduct a maneuver and record an image, and then continue to the next location. Upon completion of assigned missions, the satellite will slew back to point at the ground station and transmit the image data. Ground controllers also have the option to command that images be taken and stored for transmittal upon the next access to the ground station. Finally, the satellite seeks a sun-soaking orientation when not performing a tasked mission. Each of the subsystems plays a role in ensuring that the satellite can perform its primary function.

a. *Operational Modes*

The TINYSCOPE spacecraft has three operational modes.

NORMAL Mode is the standard operational mode for the spacecraft. In this mode the spacecraft can perform image collection and all of the supporting tasks that are required.

SAFE Mode provides a safe haven for the spacecraft when required by environmental conditions or anomalies. This mode is designed to allow the spacecraft to maintain limited functionality but still protect components from damage. In this mode, the spacecraft can no longer perform image collection. The payload and S-band radio are deactivated and the spacecraft seeks an orientation to allow the solar arrays full access to the sun. The beacon radio transmits continuous telemetry data through the omni-directional antenna. Recovery from SAFE mode requires intervention from the ground.

EMERGENCY Mode is used when the spacecraft is in immediate danger of a critical failure or mission ending damage. All subsystems with the exception of the beacon radio are deactivated. The beacon transmits a periodic distress signal along with telemetry data to preserve power. The EPS deactivates, as well as provides a direct path from the solar array to the battery for charging. The spacecraft is not capable of image collection, high rate communication, or attitude control in EMERGENCY Mode. Recovery from this mode requires that the ground station intervene by sending a hardware command to the beacon radio to reactivate the processor and load a software update.

b. **Telemetry, Tracking, and Command (TT&C) Operations**

TINYSCOPE has two antennas, one directional and one omni-directional to transmit and receive TT&C data. The S-Band transceiver periodically transmits telemetry data through the omni-directional antenna regardless of the satellite's position relative to the ground station. Telemetry data includes position, orientation and state of health information. During normal operations, the satellite will perform a slew maneuver to orient the high gain antenna towards the ground station thirty minutes prior to contact and remain in this attitude. It will then transmit a pulsed tone to allow the ground station antenna to track. Upon initial contact with the ground station, the TINYSCOPE satellite will send recorded telemetry data to the ground station and then standby for command uplink. Command uplinks will include clock synchronization, authentication and a command script. The TINYSCOPE satellite will authenticate all command uplinks before execution.

c. **Data Operations**

The TINYSCOPE spacecraft has the capability to store three types of data. Command sequence data tells the spacecraft which missions and maintenance activities to conduct. Telemetry data are gathered from each subsystem. It is essentially a log of functions performed, system status and environmental conditions. Mission data are the images that the satellite collects. Each type of data is stored in separate partitions on the solid state recorder. When the spacecraft is commanded to downlink stored data,

telemetry data are transmitted first followed by already executed and unexecuted command sequence data and then mission data. Individual images are treated as separate files by the spacecraft. Upon receiving acknowledgement that data has been received, the spacecraft will free the data to be overwritten on the solid state recorder. If a file is not acknowledged by the end of the contact, the spacecraft will retransmit the entire file at the next contact.

d. Pointing Operations

The TINYSCOPE spacecraft is attitude stabilized in three axes by the ADCS subsystem. Position and attitude determination is performed continuously by the spacecraft. Pointing control of TINYSCOPE is provided autonomously by the spacecraft processor. The processor gathers data from attitude and position sensors and pointing commands from the ground, determines the required momentum adjustment and issues commands to actuators.

Slews are vehicle maneuvers that orient the spacecraft to collect mission data, to communicate with the ground via the high gain antenna, and to orient the spacecraft for power management operations. The spacecraft uses momentum management to perform slew maneuvers. Slews may be initiated autonomously by the spacecraft or by command from the ground. A typical slew maneuver begins with a real-time or sequenced command to collect an image of a ground target. The spacecraft will perform constraint checks for sun avoidance and then point to the calculated position on the earth's surface and then settle. Settling time allows the attitude determination subsystem to

reacquire position and attitude knowledge. The spacecraft then uses fine momentum adjustments to maintain the target in the center of the image field and to null the effects of motion. Errors may be generated, if pointing to the target would violate a constraint, or if the calculated slew profile will cause the momentum stored by the reaction wheels to exceed predefined limits. In these cases, the spacecraft will unload momentum by magneto-torquers prior to the maneuver or not execute the command.

e. *Power Management Operations*

Power management functions for the TINYSCOPE spacecraft will be handled autonomously by the EPS subsystem. The power controller will regulate power to spacecraft subsystems. It will manage loads based on the spacecraft's operating mode and power profiles. The controller will also provide automatic charge of the batteries. When the spacecraft is not actively pointing for imagery collection or communications, the spacecraft will orient the solar array panels towards the sun to allow the batteries to charge.

2. Ground Systems Operations

The end user for the TINYSCOPE satellite will be the student and faculty population at the Naval Postgraduate School. Imagery may be used for research in the field of remote sensing. Archived imagery may also be available to the general public through the internet. Generally, imagery will be requested through a proposal to the activity planning element, the flight operations element will generate the commands required to execute the proposal

and the data management element will archive, process and distribute the images. This sequence may be categorized into Pre-mission Operations, Mission Execution, and Post-Mission Operations.

a. Premission Operations

Premission Operations includes activities necessary to solicit, review and approve proposals for imagery, schedule mission and maintenance activities, and conduct long range planning.
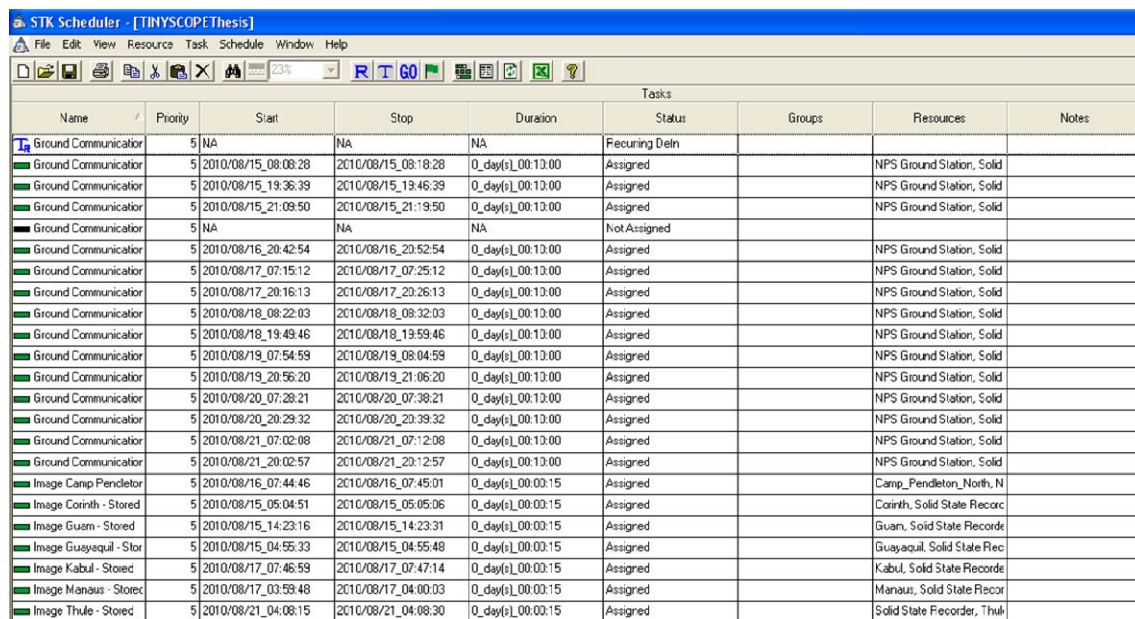
TINYSCOPE is expected to have excess capacity for image requests after commissioning and pre-planned proof of concept tests have been completed. In this instance, additional requests for imagery will be solicited. Research proposals from NPS students and faculty will likely be accommodated first, but there may be an opportunity to use some of the excess capacity for Science, Technology, Engineering, and Mathematics (STEM) outreach programs with local schools.

Regardless of the source, proposals for collection will contain basic information on the research objective, requested location, constraints on viewing geometry and weather, and how the image will be distributed. The activity planning element of the MOC will conduct monthly boards to review proposals. The board will ensure that the requested image is not militarily sensitive and that it does not violate the Land Remote Sensing Policy Act of 1992. Proposals will then be prioritized based on requested time constraints and the board's view of the proposal's merit. Finally, the

prioritized list of proposals to be scheduled will be approved by the supervising faculty member and archived by the data management element.

The activity planning element is also responsible for scheduling via the spacecraft mission plan and a detailed activity plan. Approved proposals and spacecraft maintenance activities will be scheduled in the mission plan based on priority and availability of appropriate viewing geometry. The mission plan identifies primary activities for the activity plan, special considerations or constraints, and viewing geometry.

The mission plan is translated into an activity plan depicting resource allocation, event durations and times. The activity plan is a detailed minute by minute ordering of an event sequence. An activity plan, like the one shown in Figure 13, will go directly to the flight operations element for command sequencing.

STK Scheduler - [TINYSCOPEThesis]

File Edit View Resource Task Schedule Window Help

Tasks

Name	Priority	Start	Stop	Duration	Status	Groups	Resources	Notes
Ground Communication	5	NA	NA	NA	Recurring Defn			
Ground Communication	5	2010/08/15_08:08:28	2010/08/15_08:18:28	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/15_19:36:39	2010/08/15_19:46:39	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/15_21:09:50	2010/08/15_21:19:50	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	NA	NA	NA	Not Assigned			
Ground Communication	5	2010/08/16_20:42:54	2010/08/16_20:52:54	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/17_07:15:12	2010/08/17_07:25:12	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/17_20:16:13	2010/08/17_20:26:13	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/18_08:22:03	2010/08/18_08:32:03	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/18_19:49:46	2010/08/18_19:59:46	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/19_07:54:59	2010/08/19_08:04:59	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/19_20:56:20	2010/08/19_21:06:20	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/20_07:28:21	2010/08/20_07:38:21	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/20_20:29:32	2010/08/20_20:39:32	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/21_07:02:08	2010/08/21_07:12:08	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Ground Communication	5	2010/08/21_20:02:57	2010/08/21_20:12:57	0_day(s)_00:10:00	Assigned		NPS Ground Station, Solid	
Image Camp Pendleton	5	2010/08/16_07:44:46	2010/08/16_07:45:01	0_day(s)_00:00:15	Assigned		Camp_Pendleton_North, N	
Image Corinth - Stored	5	2010/08/15_05:04:51	2010/08/15_05:05:06	0_day(s)_00:00:15	Assigned		Corinth, Solid State Recorc	
Image Guam - Stored	5	2010/08/15_14:23:16	2010/08/15_14:23:31	0_day(s)_00:00:15	Assigned		Guam, Solid State Recorde	
Image Guayaquil - Stor	5	2010/08/15_04:55:33	2010/08/15_04:55:48	0_day(s)_00:00:15	Assigned		Guayaquil, Solid State Rec	
Image Kabul - Stored	5	2010/08/17_07:46:59	2010/08/17_07:47:14	0_day(s)_00:00:15	Assigned		Kabul, Solid State Recorde	
Image Manaus - Stored	5	2010/08/17_03:59:48	2010/08/17_04:00:03	0_day(s)_00:00:15	Assigned		Manaus, Solid State Recor	
Image Thule - Stored	5	2010/08/21_04:08:15	2010/08/21_04:08:30	0_day(s)_00:00:15	Assigned		Solid State Recorder, Thul	

Figure 13.   TINYSCOPE Activity Plan

42

Long Range Planning is performed to optimize use of the spacecraft and minimize scheduling conflicts due to planned maintenance operations.

b. *Mission Execution*

The flight operations element of the Mission Operations Center performs mission execution functions. The activity plans that are generated by the activity planning element are converted into command loads for uplink to the spacecraft. Command loads may contain event commands, which instruct the spacecraft to collect an image of a specific location at a given time, or they may be system commands. System commands are instructions for the spacecraft to perform a non-collection task. Examples of system commands include instructions to transmit stored data, acknowledgements that files are have been received, commands to unload momentum and the like.

TINYSCOPE is being developed as a demonstration of immediately available satellite imagery tasking. This requires that event commands may be transmitted in real time and executed immediately. Real-time event commands are the primary type of command for the TINYSCOPE system. System commands may also be used real-time. When multiple real-time commands are sent to the satellite, they will be grouped into a real-time command script and transmitted as a batch.

It may also be necessary for the satellite to store cued commands to image locations that are not in the access footprint of the NPS ground station. In this case, a stored event command will be used. Stored command sequences are a collection of stored event and system

commands that will be executed at a later point.   Each command contains a time tag to tell the satellite processor at what time to execute the command.

A final type of command that may be used is the software update command. Software update commands load updated databases or software patches to the satellite processor.   These might include updates to star databases, ephemeris tables or corrections to flight software.

Regardless of the type of command that is being sent to the satellite, it must be reviewed and then tested on a software model of the fight system.   Once a command sequence or real-time script has been validated, it will be given an authentication tag by the simulation software. Upon uplink the satellite will verify the authentication tag prior to executing any command.   Validated and authenticated command files will be sent to the ground station computer and will be transmitted automatically following contact with the spacecraft.

c.   Post-Mission Operations

Following a successful contact with the ground station, telemetry and imagery data that was broadcast by the spacecraft will be transmitted automatically to the flight operations element.   Files will be checked for integrity and then relayed to the data management element.

Engineering and telemetry data will be processed in the flight operations element and simultaneously archived by the data management element. The flight operations element will analyze telemetry logs to monitor

the spacecraft's state of health, discover anomalies and identify trends that may degrade operations.

Mission data will be passed to the data management element for processing and archiving. Raw copies of the image will be stored in a separate image database from images that have been processed. Images that were collected following an accepted research proposal will be provided to the researcher in raw format. Public access to processed images may be available via the internet at the discretion of the university. Raw data may also be made available for a fee to defray processing expenses. Occasionally the flight operations center will review raw images to identify CMOS pixels that are not functioning properly. Pixel information will be passed to data processors to aid in removal of incorrect information.

3. Launch and Early Operations

Launch and early operations (L&EO) includes launch, activation and commissioning.

a. Launch Operations

Launch Operations begin at lift-off and end when the spacecraft has been ejected from the CubeSat deployer. CubeSats are typically secondary payloads and launch opportunities in a particular orbit are not guaranteed. Secondary payloads have additional constraints that are required as well. During launch operations the spacecraft will be safed and unpowered. This requires that the spacecraft have a means of self-activation.

b.   Activation Sequence

The TINYSCOPE spacecraft will be activated by the release of a spring-loaded contact pin when it is pushed from the deployment assembly. Activation will initiate a sequence of events, as shown in Figure 14. The critical events in the sequence are depicted in bold outlines and include: attitude stabilization, solar power generation, and initiation of low rate communications.

c.   Commissioning

Following activation, the TINYSCOPE spacecraft will enter a commissioning phase during which all of the spacecraft subsystems will undergo testing to ensure full operability and the payload will be powered on for the first time. The objective of commissioning is to achieve a status that allows normal operations.

The first task in the commissioning phase is gaining fine pointing control of the spacecraft. This requires several steps. Initially, the spacecraft will perform a series of predefined momentum adjustments to confirm and refine the spacecraft's moments of inertia. The refined MOIs will be fed into the spacecraft control algorithms during a software update. The various instruments used for attitude and position knowledge will be calibrated and ephemeris will be updated. Finally, attitude control parameters will be finely calibrated by using a series of slew maneuvers that gradually increase in aggressiveness.

A second task that will be performed simultaneously during commissioning is verification and

calibration of bus subsystems. Power generation, temperatures, and electrical loads will be monitored to generate baseline profiles for the spacecraft. Autonomous operations parameters, fault detection triggers, and fault response mechanisms will be updated as necessary based on the baseline profiles. Bit error rates will be determined for the spacecraft to ground communications links as well.

The final commissioning task is activation, checkout, and performance evaluation of the optical payload. Activation will occur after a wait period to allow out-gassing to occur. The camera module will be powered and functional tests will be performed. Electronic calibration will be performed to ensure the health of the detection lines. Once the camera is determined to be operating properly, the spacecraft will be tasked with a series of reference missions to determine performance levels. These missions will use a variety of locations to measure pointing accuracy, uniformity of the CMOS detector response, and resolution.
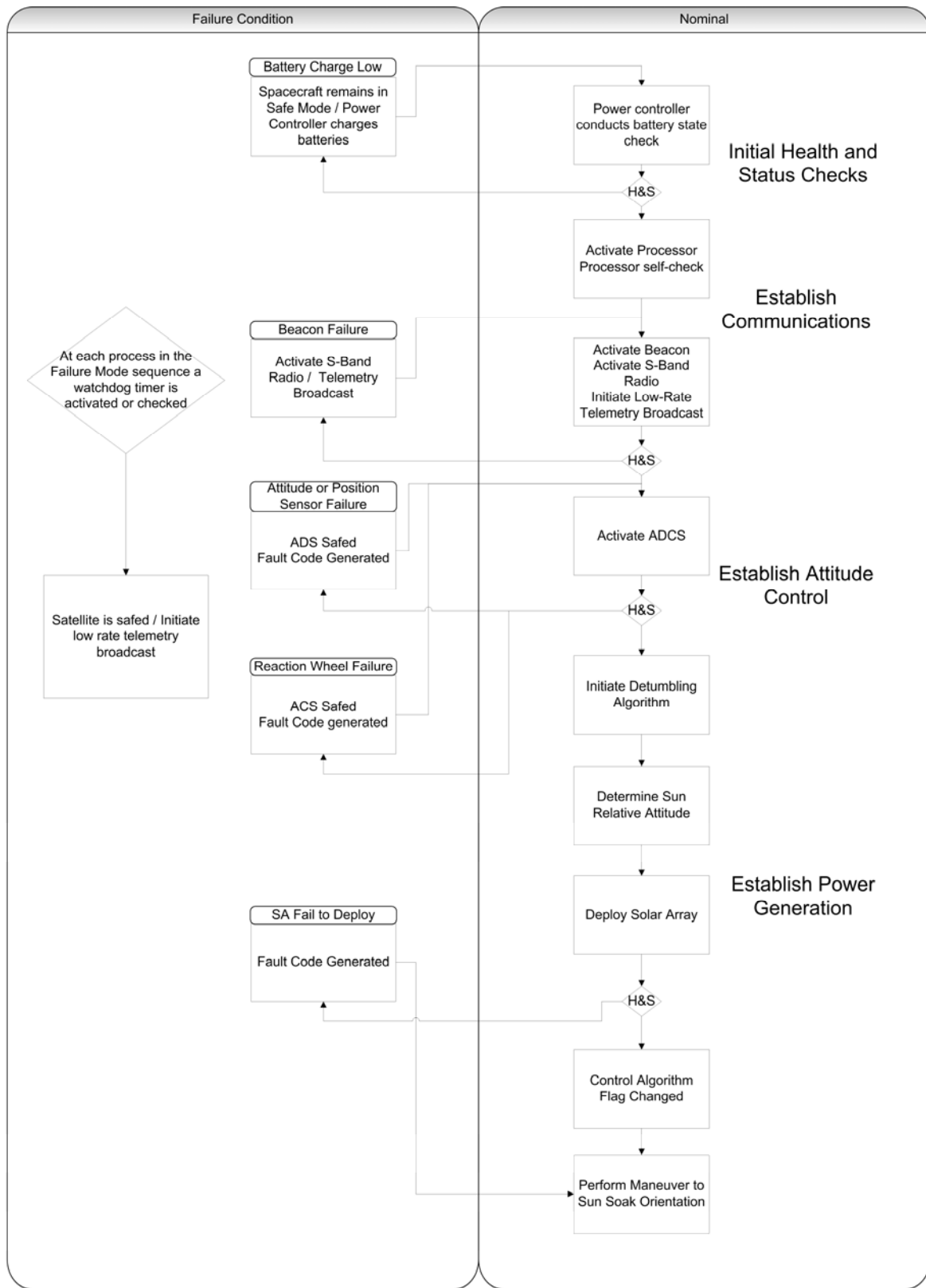
Figure 14.   Spacecraft Activation Sequence

C. NORMAL OPERATIONS

1. Contact Scenario

a. *Objective*

This scenario describes the functions performed during a standard communications contact between the TINYSCOPE satellite and the ground station. These functions will be automated during nominal passes.

b. *Assumptions*

- This is a standard pass over the NPS ground station. Access time will be greater than 4 minutes.
- Satellite ephemeris at ground station and on-board is accurate to within two and one half degrees.
- Satellite beacon and S-band radio are operational.
- Command script has been developed, authenticated and has been received by the ground station computer.

c. *Description*

Thirty minutes prior to contact the TINYSCOPE spacecraft will slew to point the high gain antenna at the ground station and will maintain track. The ground station antenna will steer to predicted contact point.

Fifteen minutes prior to scheduled contact the spacecraft will begin to transmit continuous low rate telemetry data through the omni-directional antenna. The ground station antenna will initiate a sweep pattern to acquire the beacon.

Upon acquisition of the beacon, the ground station will begin tracking and transmit a handshake

signal.   The spacecraft will maneuver as necessary and complete the handshake with the S-band radio and high gain antenna.   The beacon will then cease to transmit. Following handshake, the spacecraft will pass real time telemetry to the ground station.   The ground station will upload a clock synchronization command followed by the authenticated command script.

A typical command script will contain a command to initiate playback and a new command load. Playback will begin with the telemetry log followed by the command sequence data and mission data.   Data will be packetized to protect against communications disruption.

Ninety seconds prior to the contact keyhole time the ground station will send a command to halt playback and begin beacon operations.   The handshake process will restart as the keyhole period ends and another playback command will be sent. This sequence will occur again at the end of the contact period.

After completion of playback or loss of contact, the satellite will terminate the S-band transmission and resume normal operations.   The ground station antenna will steer back to its stowed position and data will be transferred to the flight operations element.
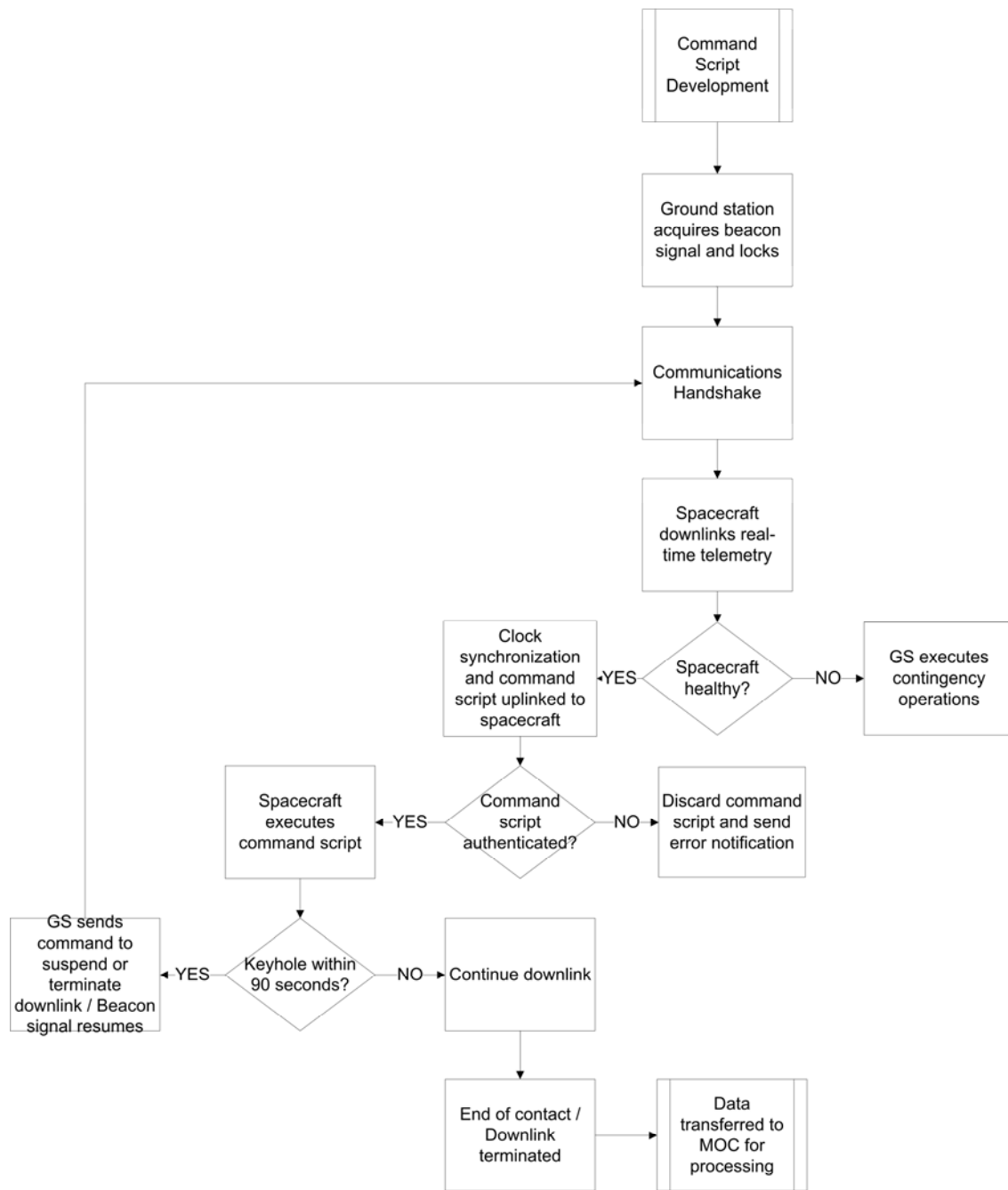
d.   Flow Diagram

Figure 15.   Nominal Contact Scenario

2. Real Time Collection Scenario

a. Objective

The primary mission of TINYSCOPE is real-time image collection. This scenario describes the system's performance when a real-time event command script is uplinked following contact.

b. Assumptions

- The flight operations element has constructed an authenticated command load sequence that has been received by the ground station computer.

- Spacecraft and ground station have performed handshake and spacecraft is prepared for command script uplink.

c. Description

The real time collection profile begins with the uplink of the command script to the spacecraft. Real time command scripts contain an immediate execution tag. Upon recognition of this tag, the spacecraft will terminate S-band transmission and resume low rate telemetry broadcast by the beacon. This allows the flight operations element to monitor the mission.

The spacecraft processor determines the required momentum adjustments to maneuver the spacecraft to point at the desired location and executes the maneuver. Simultaneously the camera instrumentation will be activated. As the spacecraft approaches the correct orientation the adjustments become finer to allow the spacecraft to settle. Additional fine adjustments will be conducted during camera operation to reduce motion blur.

The camera will record the target image onto the solid state recorder. The spacecraft will repeat this sequence for additional tasked images and then return to an orientation to communicate with the ground station.

The S-band radio will be reactivated after the handshake with the ground station and the contact scenario will resume.
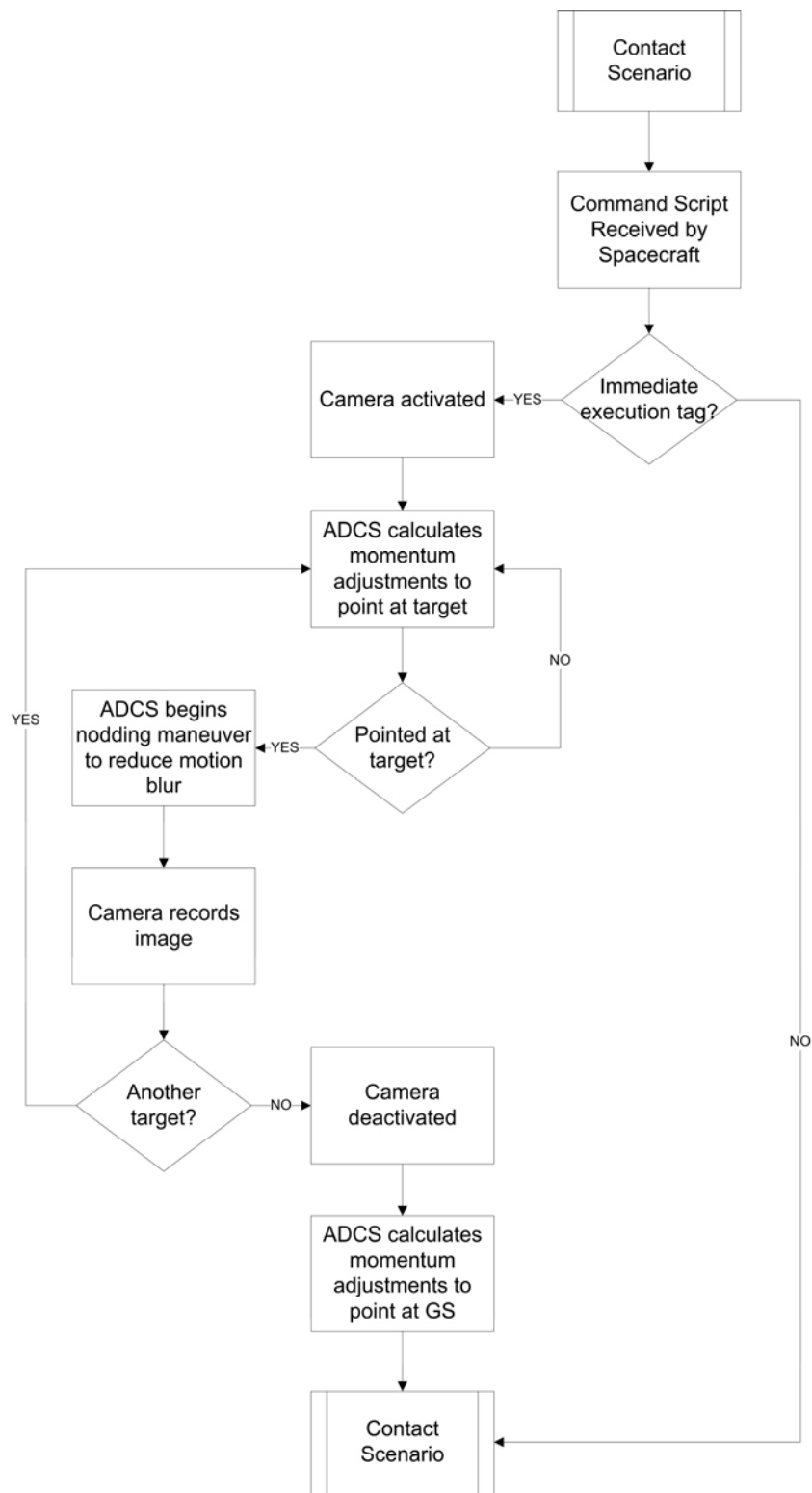
d. Flow Diagram

Figure 16. Real-Time Collection Scenario

3. Programmed Collection Scenario

a. *Objective*

This scenario describes the system's performance when a stored command sequence is uplinked following contact.

b. *Assumptions*

- The flight operations element has constructed an authenticated command load sequence that has been uplinked to the spacecraft.

c. *Description*

Execution of a stored command sequence begins after the termination of the contact scenario. The spacecraft begins by ordering the commands based on the time tags in the command sequence and discarding any commands that have expired.

The spacecraft then identifies the command with the earliest time tag. If the time to event is greater than fifteen minutes, then the spacecraft will execute a maneuver to a sun-soaking orientation. Fifteen minutes prior to execution of a command, the spacecraft will begin momentum adjustments to point the spacecraft at the target. As the spacecraft approaches the correct orientation, the adjustments become finer to allow the spacecraft to settle. Additional fine adjustments will be conducted during camera operation to reduce motion blur. The camera will record the target image onto the solid state recorder. The spacecraft will repeat this sequence for additional stored events, returning to a sun-soaking orientation as allowable.

d.   Flow Diagram

Figure 17.   Programmed Collection Scenario

4. Momentum Management Scenario

a. *Objective*

This scenario describes the process required to unload momentum from the reaction wheels as they become saturated.

b. *Assumptions*

- Momentum unloading may occur autonomously or as part of a command load.
- No image collection will take place while the spacecraft is unloading momentum

c. *Description*

The reaction wheels on the TINYSCOPE spacecraft will become saturated as the wheels reach their maximum spin rates. Momentum unloading will occur when any reaction wheel becomes 80% saturated. Magneto-torquers will be used to dump the momentum.

The momentum management scenario is started by a command from the ground or when telemetry indicates that the saturation threshold has been met. Collection operations will be suspended. Stored commands will be reordered if possible. Real time commands will be discarded and an error will be annotated on the telemetry log.

The magneto-torquer orthogonal to the most saturated reaction wheel will be activated. That reaction wheel will then be decelerated to zero. This sequence will be followed by the next two reaction wheels. Following unloading, the spacecraft will resume normal operations.
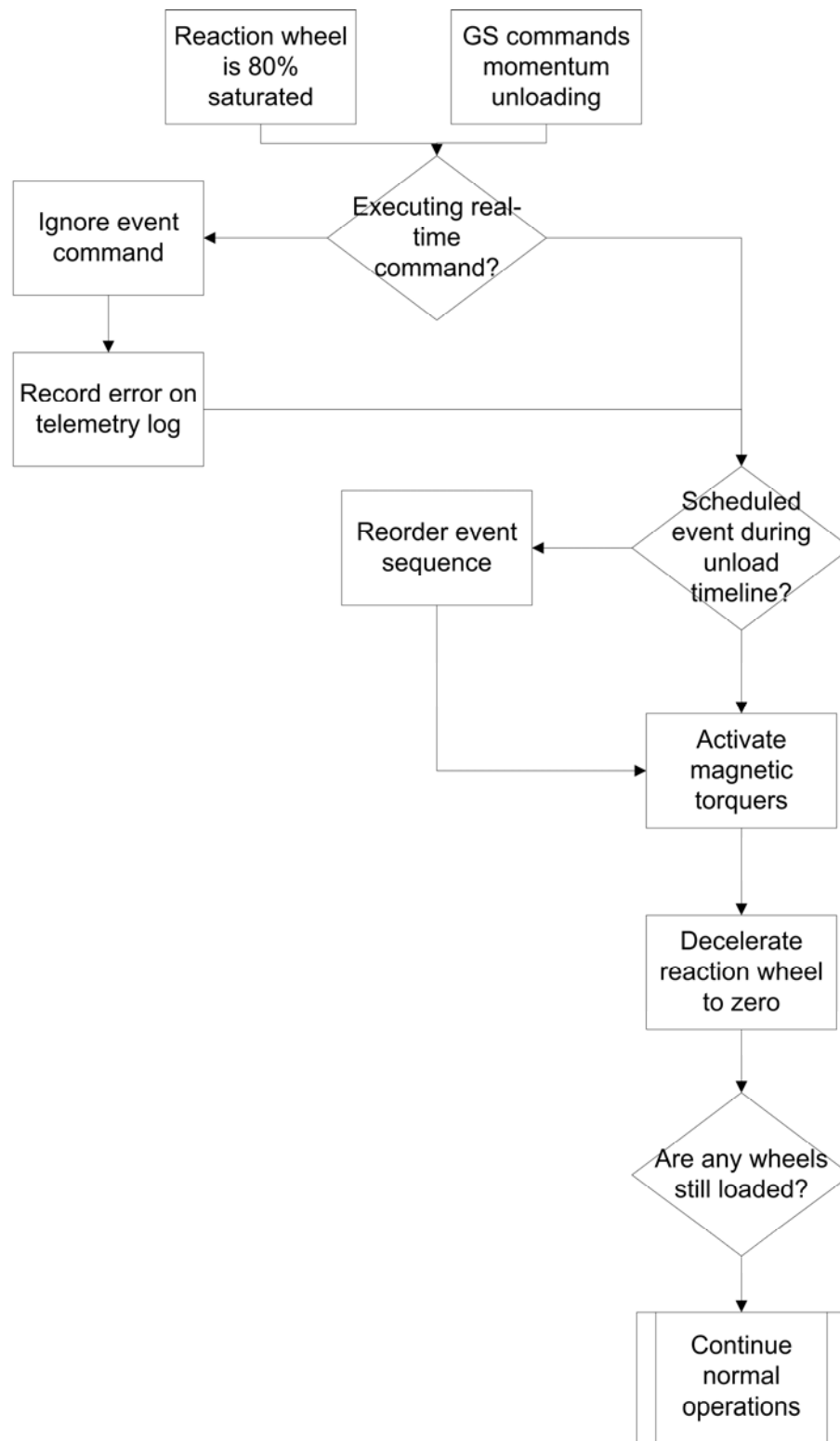
d.   Flow Diagram

Reaction wheel is 80% saturated

GS commands momentum unloading

Executing real-time command?

Ignore event command

Record error on telemetry log

Scheduled event during unload timeline?

Reorder event sequence

Activate magnetic torquers

Decelerate reaction wheel to zero

Are any wheels still loaded?

Continue normal operations

Figure 18.   Momentum Management Scenario

58

5. Software Update Scenario

    a.   Objective

This scenario describes the process of updating the spacecraft's flight software. A software update may be required to correct a bug or to update the star tracker database or ephemeris tables.

    b.   Assumptions

- The processor being updated is functioning properly.
- The software update has been tested on the software simulator.
- Spacecraft and ground station have performed handshake and spacecraft is prepared for command script uplink.

    c.   Description

Software uploads have the potential to be catastrophic. The TINYSCOPE solid state recorder has two partitions dedicated to flight software integrity. The partition in which the current version of flight software being used by the processor resides is designated as the primary partition. The secondary partition alternately stores a past version of a future version.

Software update procedures begin with the uplink of a preparatory command to delete the secondary partition. The new flight software is then transmitted to the spacecraft and stored in the secondary partition.

Software update files are transmitted in packet segments that include cyclic redundancy checks (CRC) at the frame level. Additionally, a file checksum is used to compare the completed file on the spacecraft with that on

the ground. If a CRC fails, the entire packet is retransmitted. If a file checksum fails, the entire file will be retransmitted.

Once the software update is in pace in the secondary partition and integrity checks have passed, a command to execute memory load will be transmitted. The update will be copied completely to the processor memory load buffer and integrity checks will be performed again. If a check fails the load buffer will be erased and an error report sent to the telemetry log and the ground station. If the integrity checks pass, the memory load will continue. After the memory load is complete the load buffer will be erased and a completion message will be sent to the telemetry log and to the ground station. The processor will then run a diagnostic self-test to ensure full functionality. Upon successful completion of the test, the secondary partition will be designated as the primary and vice versa.

If the processor fails a diagnostic test or the software is discovered to have errors, the previous version may be recovered from the secondary partition without contact with the ground.
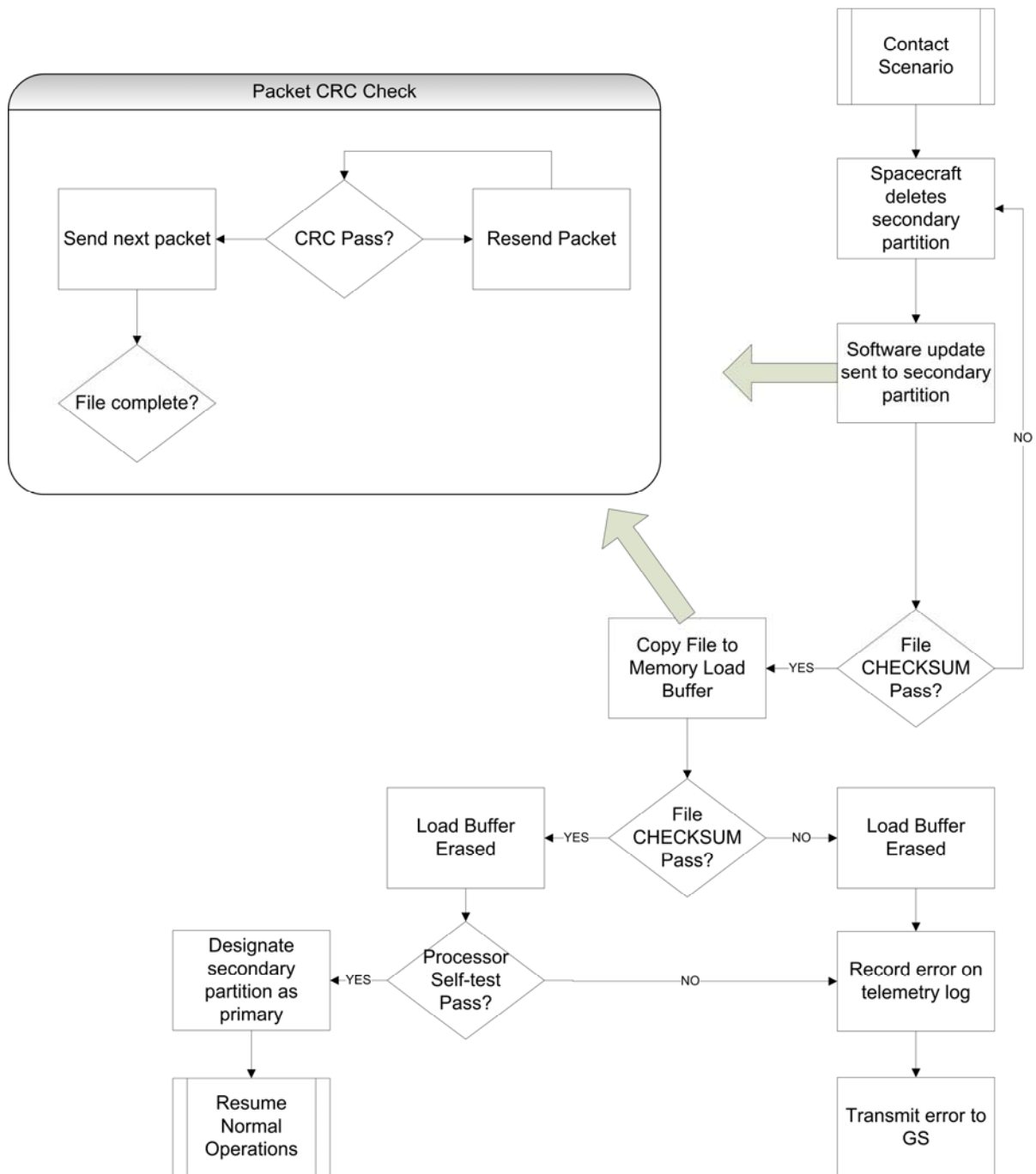
d. ***Flow Diagram***

Figure 19. Software Update Scenario

D.   CONTINGENCY OPERATIONS

1.   Fault Detection

a.   Objective

The flight processor monitors each subsystem's operational status to record in the telemetry log and to check for anomalies. If an anomaly is discovered, it may require the satellite to end normal operations to protect the subsystem from damage. This scenario describes how the processor monitors and examines the subsystems.

b.   Assumptions

- The spacecraft is operating in normal operations mode.

c.   Description

The flight processor automatically responds to anomalies on the spacecraft. The response to a given anomaly has usually been predetermined and tested prior to launch. Anomaly responses are integral to the flight software and changes to responses will require a software update. In the event that an anomaly occurs that the spacecraft does not have a programmed response for, the processor will place the spacecraft in emergency mode.

Anomalies that have been planned for may be responded to by taking the reporting subsystem offline, placing the satellite in safe mode or by simply reporting the anomaly to the telemetry log. The severity of the anomaly will typically dictate the action taken.

A subsystem may be taken offline when there is a condition that will cause further damage to the subsystem or the spacecraft if not corrected. An example of this

type of condition would be a temperature or voltage measurement that is too high or low causing a component to overheat or drain power from the spacecraft.

The satellite will be placed in a safe mode when failure to respond will endanger the mission. This may occur when an anomaly involves more than a single subsystem or when the anomaly indicates that a reaction wheel of the spacecraft is out of limits.

Minor anomalies or pseudo-anomalies may require only that the anomaly is reported. Example cases of a report only anomaly may include failure of the battery to fully recharge or a slow rise or fall in temperature that is creating a thermal imbalance.

Anomalies that involve the safing of the satellite or a subsystem must be resolved before normal operations can begin again. These anomalies will be analyzed by the flight operations element and corrective actions will be fully tested on simulator software before implementation.

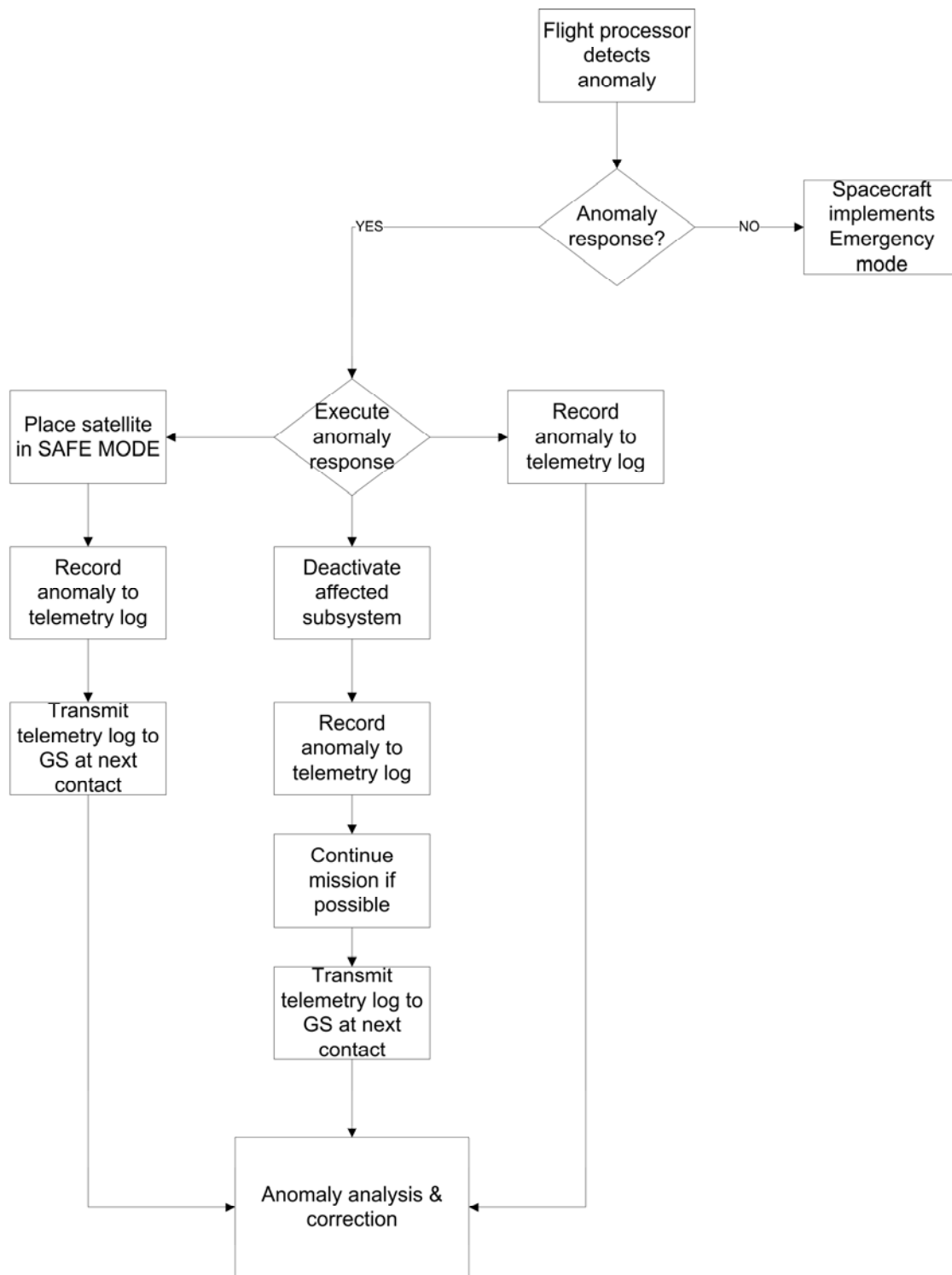***d.*** ***Flow Diagram***

Figure 20. Fault Detection Scenario

2.   Power Management Failure Scenario

a.   *Objective*

This scenario describes the autonomous response of the spacecraft when the EPS reports a low power condition.

b.   *Assumptions*

- The spacecraft is operating in normal operations mode.
- The EPS, solar array and batteries are fully functional.

c.   *Description*

The EPS on TINYSCOPE continuously monitors the battery state of charge and the power drawn by the spacecraft's subsystems. A low power contingency may occur, if the spacecraft has been performing excessive attitude maneuvers in support of normal operations and has not maintained an orientation that allows power generation. When the batteries reach a low state of charge, a fault will be reported to initiate the automatic response. The spacecraft will cease to execute event commands and will go to SAFE Mode. The EPS will shunt all power to the batteries in an effort to allow them to recharge. The EPS will automatically restore normal power when the battery state of charge recovers satisfactorily.

A more severe fault is generated if the state of charge continues to fall to a critical level. At this point, the spacecraft will go to EMERGENCY mode. Recovery from EMERGENCY mode requires intervention from the flight operations element.
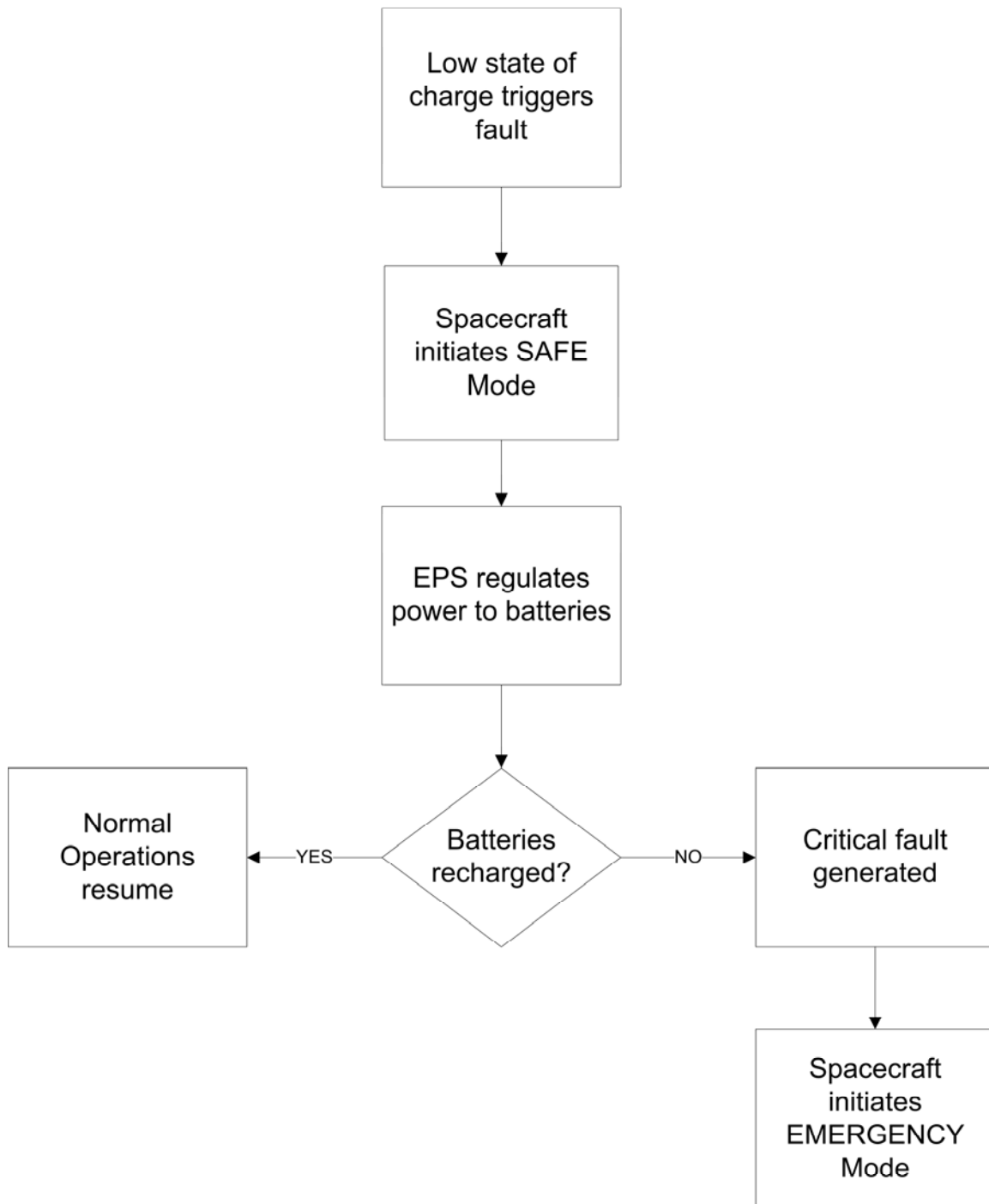
d. *Flow Diagram*

Figure 21.   Low Power Scenario

3.   **Loss of Low-Rate Telemetry Beacon Scenario**

   a.   *Objective*

   This scenario describes the procedures taken when the low rate telemetry beacon fails resulting in the inability to acquire a signal for the GS antenna to lock onto.

   b.   *Assumptions*

   - There is a scheduled contact with the ground station. Spacecraft was operating normally during last contact.
   - Ground station antenna and computer are operational and pointing correctly.
   - All other spacecraft systems are functioning properly.

   c.   *Description*

   As in the contact scenario, the GS antenna will steer to and point at the location where the spacecraft is predicted to be. During a nominal contact, the antenna would acquire the beacon signal and use it to lock onto the satellite to enable high gain antenna communications. When the beacon signal cannot be located using the standard search pattern, this procedure is used.

   The flight operations element will verify that the GS is operational and is not at fault for the lack of acquisition. Pointing angles will be recalculated and verified in the GS computer. Command logs from the previous contact will be examined to ensure that the problem was not induced by a command. Telemetry logs will be reviewed for anomalous conditions and to ensure that

67

ephemeris data is correct. If the condition remains, the fault will be assumed to reside with the spacecraft.

The GS will transmit a command to the spacecraft to activate the S-band transmitter and high gain antenna and commence downlink of telemetry data. This command will be repeated during subsequent passes until communications with the spacecraft is restored. Simultaneously, the flight operations element will begin developing a command load sequence to bypass the beacon and omni-directional antenna and utilize the S-band radio and high gain antenna for telemetry broadcast. Once communications can be restored, the alternate contact sequence will be used until the anomaly can be corrected.
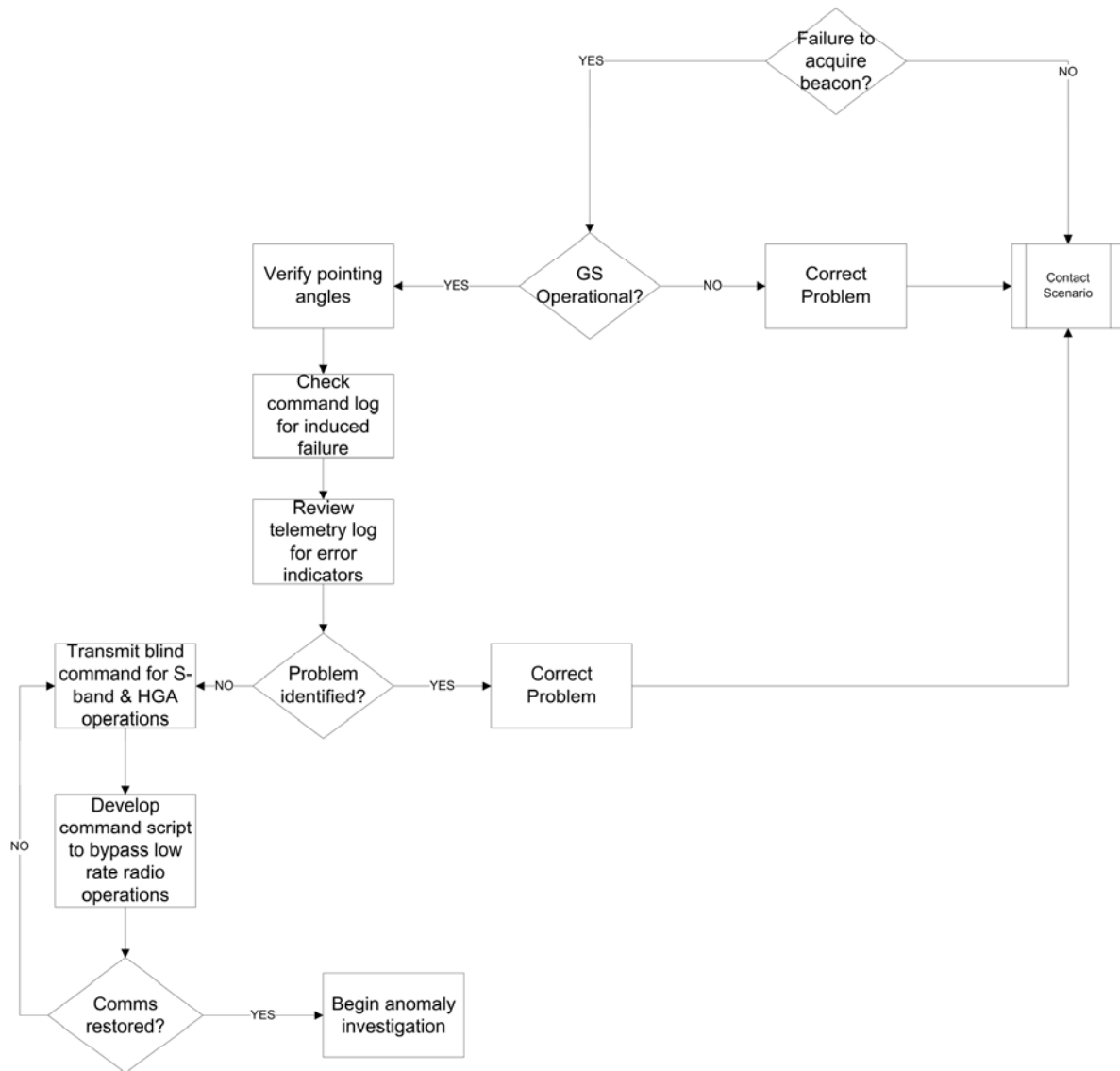
d. *Flow Diagram*

Figure 22.   Beacon Acquisition Failure

4. **Loss of Command Ability Scenario**

    a. *Objective*

This scenario describes the procedures taken when the S-band radio or high gain antenna fail resulting in a loss of ability to command the spacecraft.

    b. *Assumptions*

- The spacecraft is operating in normal operations mode.
- Beacon signal has been acquired and GS antenna is locked on the satellite.
- Last contact with spacecraft was nominal.

    c. *Description*

The S-Band radio and high gain antenna are the primary means of communication with the TINYSCOPE spacecraft. Should one or both fail, the spacecraft may be commanded through the low rate telemetry beacon. It is also possible for the spacecraft to transmit mission data through the beacon, but the data rates would be sub-optimal.

During a nominal contact scenario, the ground station will lock onto the satellite using the beacon and then upload commands and download data using the S-band radio and high gain antenna. Indications that there is an anomaly with these components may come through a communications handshake failure.

When an anomaly exists, the flight operations will first verify that the ground station is operational and is transmitting in the appropriate band and frequency. If the problem persists, a series of innocuous command will

70

be transmitted to the spacecraft to determine if the spacecraft can receive transmissions. The low rate telemetry being broadcast by the beacon should change based on the commands that were sent.

In the event of a transmit only failure, the satellite will be commanded to downlink the telemetry and command sequence logs through the beacon and will be placed in SAFE mode. Anomaly investigation and fault recovery procedures will be implemented.

A lack of change in the telemetry following the test commands indicates that there is a receive failure. A hardware command will be sent to the beacon radio to send a fault code to the processor. The processor will then use its programmed response to deactivate the S-band radio and transmit and receive using only the beacon and omni-directional antenna. The satellite will then be placed in SAFE mode and anomaly investigation and fault recovery will begin.
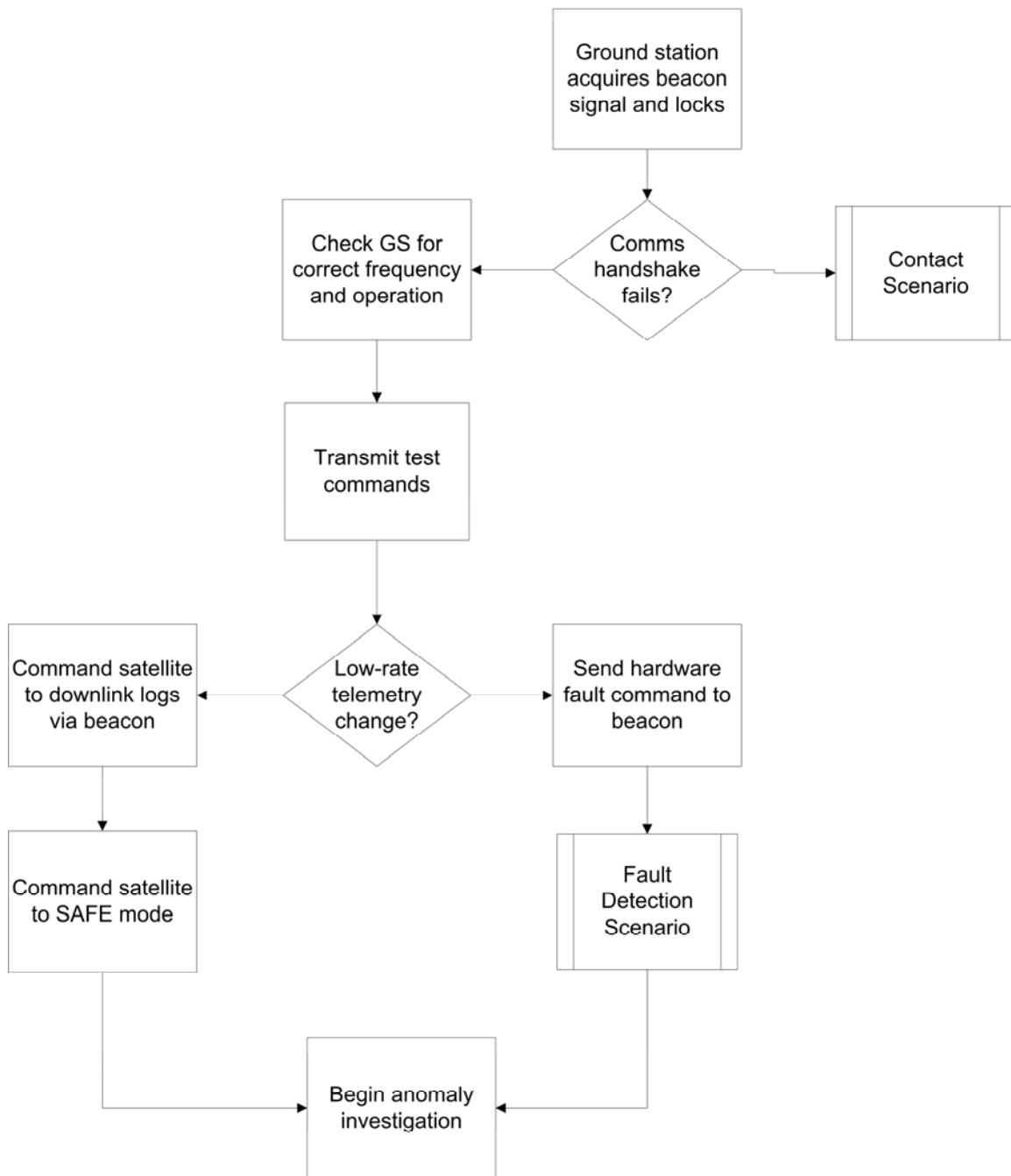
d. Flow Diagram

Figure 23.   Command Failure Scenario

E.   INTEGRATION AND TEST

1.   System Integration and Functional Tests

The TINYSCOPE satellite will undergo integration and testing in a Class 6 (ISO) clean room to ensure the spacecraft is not damaged by particulates.   Equally important is that working in a clean room environment impresses upon students and others that the processes and activities are now such that a higher level of attention and consequence must be kept in mind while working with the hardware.   Integration begins with the mating of the payload to the bus assembly and subsequent alignment. Mass models of the solar arrays will be added for some testing. This is Stage 1 for testing purposes.   At Stage 1, the satellite will undergo a functionality test of all the mechanisms. The ADCS will be tested using simulated state vectors to ensure proper motion of the reaction wheels. The spring-loaded activation switch will be tested to ensure proper operation and solar array hinges and actuators will be tested. A telemetry check will be performed using simulated data. The satellite will be placed in the three-axis simulator and control algorithms and moments of inertia for both deployed and non-deployed solar panels will be verified. Finally, the systems fault detection and responses will be tested using induced faults.

The solar array panels will be integrated with the system for Stage 2 testing. During this stage, electrical interfaces will be verified and environmental testing will occur.

2.   System Environmental Testing

Environmental testing for the spacecraft will consist of thermal vacuum testing, electromagnetic interference testing (EMI), and random vibration testing.

Thermal vacuum testing will be used to identify workmanship deficiencies under flight-like conditions and to screen for out-gassing and current arcing.

EMI testing will verify compatibility of the subsystems' radiated emissions. During this test, each subsystem will be operated in its most noisy state to determine interference with other subsystems.

Random vibration testing will verify the system's ability to withstand the vibroacoustic environment of the launch. It will also help to identify workmanship deficiencies [15].

IV. CONCLUSION

A. SUMMARY

The program management and systems engineering challenges and lessons outlined in this thesis should be a useful guide for future projects at the Naval Postgraduate School. In the author's opinion, the success of a project is determined largely in the planning stage.

A good program will have a clear end state and the milestones required to achieve that end will be defined in a framework document. System requirements must be clear, concise, and verifiable. Cost, performance, schedule and risks must be monitored continuously throughout the project and in accordance with the framework. This program has been an excellent way to exercise the tenants of systems engineering and project management in an environment that fosters learning.

B. FUTURE WORK

The TINYSCOPE program has been an excellent learning experience. A tremendous amount of work has been conducted by the TINYSCOPE team, but much still remains to be done.

There are several management functions of the program that still require direction. The Systems Engineering Management Plan will provide a foundation for the implementation of the engineering effort by identifying the deliverables during each phase and defining the quality assurance plan and methodology for the project. It clearly outlines individual roles and responsibilities to ensure synergy among the work force. The Software Management Plan

defines the format of communications between the various subsystems. It will drive the development of the on-board algorithms, fault detection and recovery schemes, and authentication protocols for the system.

A ground system still needs to be developed to manage communications with the spacecraft, data management functions, and flight operations. The author hopes that development will be somewhat simplified by the effort given in this thesis to define the flow of operations.

Finally, there is much work that remains in the design and development of the spacecraft bus and in the testing and integration of the various subsystems. Each of the bus subsystems and the payload will require environmental and functional tests and will require modifications to integrate with the spacecraft. The bulk of the command software and any processing software that may be used must be engineered and coded. Following integration of the subsystems, the satellite will have to undergo a full battery of functional and environmental tests to ensure that it will operate as planned.

APPENDIX A – TINYSCOPE PROJECT PLAN

This document is a part of the TINYSCOPE Project Documentation, controlled by the TINYSCOPE Project Manager under the direction of the Nanosat Advanced Concepts Laboratory at the Naval Postgraduate School, Monterey, CA.

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Record Of Revisions

REV	DATE	AFFECTED PAGES	DESCRIPTION OF CHANGE	AUTHOR
A	4/28/10	All	Baseline	Chris Turner
B				
C				
D				

1 PROJECT OVERVIEW

1.1 Introduction

The TINYSCOPE Project Plan describes the activities required to implement the flight of the technology demonstrator spacecraft. The TINYSCOPE mission will be conducted in a relevant space environment as defined for a Technology Readiness Level (TRL) of 8. TINYSCOPE will both demonstrate new spacecraft technologies and implement proven technologies.

The TINYSCOPE project is primarily used as a vehicle for student research into attitude dynamics, guidance, navigation and controls algorithms and mission operations. Additionally, student researchers are gaining hands-on experience with design, construction and integration of satellite hardware. The current schedule plan is to deliver hardware ready to fly by December 2011. Due to the project's size, scope, cost and schedule, the risk constraints for the project are somewhat relaxed when compared to traditional space flight. As such qualification testing is required only for verification of safety compliance and interface compatibility with the launch vehicle adapter. Acceptance tests will be conducted to ensure that critical performance parameters are likely to be achieved. Project reviews will be performed in the context of a technology demonstration test.

1.2 Objectives

TINYSCOPE is an effort to develop a low-cost and easily replaceable imaging spacecraft that can produce tactically relevant imagery data. Tactical requirements in this context would emphasize "good enough" image resolution with a rapid-response tasking loop and high revisit rate. The TINYSCOPE project intends to demonstrate the utility of small, risk tolerant spacecraft for this purpose. The objectives of the TINYSCOPE mission are:

A. The primary objective of the TINYSCOPE program is facilitation of student education at the Naval Postgraduate School.

B. Launch and operate one TINYSCOPE spacecraft capable of obtaining images of a tasked target along a

predetermined low earth orbit and transmitting images to a known stationary ground station within minutes of tasking.

C. Demonstrate an attitude determination and control system to provide accurate and agile pointing for nanosatellites.

1.2.1 Performance Measurement System

The methodology used for managing the TINYSCOPE Project and measuring performance will be to monitor appropriate status indicators. Monthly updates reporting on risk data and the impact on mission success will be generated and tracked. The following categories will be examined monthly for risk impact.

Cost

Evaluate how the project budget is performing against the approved Project Plan budget and FY Actual vs Planned performance.

Schedule

Evaluate how the project schedule is performing to ensure major milestones and the project delivery dates approved in the project plan are met.

Technical Performance

Evaluate how the project is meeting the requirements documented in the approved project plan.

Management Issues

Evaluate management products/processes and other management responsibilities to ensure the project will meet commitments.

1.2.2 Mission Success Criteria

Objective 1 - Successful implementation and execution of the project plan including design, construction, verification, launch, on-orbit evaluation and delivery of appropriate ground control hardware.

Objective 2/3 - This system will have the ability to detumble and stabilize, point to earth and subsequently image and download to a ground station.

1.2.3 Extended Mission Success Criteria

Objective 1 - Successful completion of the development, test and integration activities results in hardware delivered for launch by December 2012.

Objective 2 - Ability to download multiple images from a single orbital pass over the known ground station. The spacecraft will continue to operate and perform mission functions for a period of three months following launch.

Objective 3 - Ability to quickly and accurately point to a specified location on the earth's surface.

1.3 Mission Description and Technical Approach

TINYSCOPE is a unique spacecraft with experimental structural and pointing requirements, optics and software. Both the payload and bus will necessarily consist of technologies with various levels of maturity and space heritage. Therefore, wherever possible it is necessary to mitigate risks to operational success and to schedule by incorporating commercially viable components, with a preference for flight proven technologies. Development of unique subsystems will be considered on a case by case basis and will only be attempted when more mature options are not viable due to cost, performance or schedule constraints. TINYSCOPE will seek to exploit the advantages of CubeSat platforms by including small subsystems requiring minimal power, mass, volume, and cost to operate.
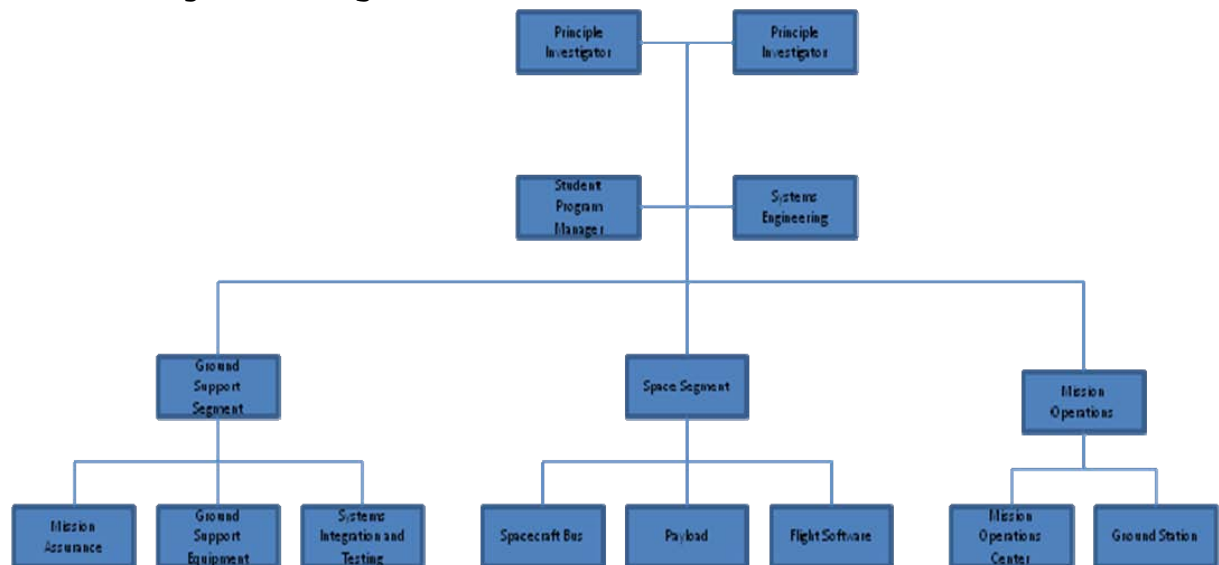
1.4 Project Management and Team Structure

Figure 24. TINYSCOPE Project Team Structure

81

1.5 Stakeholder Definition

The objectives of the TINYSCOPE Project are intended to provide a demonstration of the capabilities that small satellites can provide to national security goals. The project is a direct offshoot of thesis work performed by Allen Blocker and Chance Litton intended to further the research into alternative national security space architectures. Therefore the customers of TINYSCOPE include:

- National Reconnaissance Office
- Air Force Research Laboratory
- USSTRATCOM
- Office of Operationally Responsive Space
- External space technology R&D, commercial and academic organizations

2 PROJECT BASELINE

2.1 Requirements Baseline

The hardware shall be designed and built to meet the bus, payload, mission and technology, and master satellite interface requirements as documented in the Certification and Acceptance Requirements Document (CARD). The technology hardware shall be designed to meet the specifications for the interface requirements of the payload subsystem as well as the interface requirements of the Spacecraft Deployer and Launch Vehicle provider. Clarification of user requirements, operations, and driving technology will be performed prior to the Critical Design Review (CDR).

2.2 Reference Documents

The following documents are reference documents for this plan:

Certification and Requirements Document NACL10-02-T

Systems Engineering Management Plan NACL10-03-T

Software Management Plan NACL10-04-T

TINYSCOPE Master Schedule NACL10-05-T

Mission Operations Plan NACL10-06-T

Master Product Breakdown Structure NACL10-07-T

Contamination Control Plan NACL10-08-T

TINYSCOPE Request for Research Proposal to NRO

2.3 Product Breakdown Structure

The TINYSCOPE Project has three primary segments:

- Satellite System – This includes both the Bus and payload systems. The payload systems specifically include the telescope, image detector, associated software, data management for the payload, and supporting systems. The Bus systems include communications system, flight computer and software, power generation and distribution, attitude determination and control systems, and structural systems, including thermal management.

- Mission Operations Systems - This includes spacecraft control and flight test support Mission Operations Center (MMOC) and Ground Station.
- Ground Support Systems - This includes quality assurance, integrated testing and verification, and satellite handling.
- Detailed information defining each of the segments and related subsystems is located in the Master Product Breakdown Structure.

2.4 Schedule Baseline

The program manager and the TINYSCOPE team will use this schedules for evaluating, managing, and reporting project performance with respect to baseline plans. Lower level schedules will be developed and monitored via major milestones and interim deliverables to be determined in those detailed development schedules. Variances will be addressed as program risks if threatening Major Milestone delivery dates.

Major Milestone   Date

MRR	Mission Requirements Review and Baseline	9/15/10
PDR	Preliminary Design Review	TBD
CDR	Critical Design Review	TBD
FRR	Flight Readiness Review	TBD
	Flight Hardware Ship to Launch Site	TBD
ORR	Operations Readiness Review	TBD
	Launch Readiness Date	TBD

2.5 Resource Baseline

FY 09	Total Funding
Procurement	45,000
Labor	33,000
FY 10	
Procurement	TBD
Labor	TBD
FY 11	
Procurement	TBD
Staffing	TBD

Approval is restricted to above budget. Any deviation from the approved budget must get approval from both Primary Investigators.

3 PROJECT CONTROL PLANS

3.1 Technical, Schedule, and Cost Control Plan

Phasing will conform generally to the proposal for research submitted to the AS&T, NRO for the period October 1st, 2009 – December 31st, 2010. More specifically, the baseline schedule referenced in Section 2.5 of the Project Plan outlines the timeline of milestones and reviews. Reviews are held at the end of every phase as the control gate to end each phase as well as get approval to proceed to the next phase. The Systems Engineering Management Plan explicitly defines all deliverables for each milestone. The milestones will be used as a schedule performance metric with a recommended corrective action scheduled for each milestone past due. Lower level schedules will be developed and monitored via milestones and interim deliverables to be determined in detailed development schedules. Variances will be addressed as program risks if threatening milestone delivery dates. Cost performance metrics will consist of planned vs actual FY budget analysis performed monthly. Technical requirements will be reviewed monthly to ensure that each segment remains on track to meet performance objectives.

3.2 Mission Assurance Plan

TINYSCOPE reliability requirements support the characterization of the program as a short hardware life requirement, low complexity, low cost, short program duration, and economically replaceable. The TINYSCOPE hardware will be designed to operate for at least one complete mission cycle (minimum of 6 months) including ground operations prior to flight. The launch provider ground safety reviews will also be conducted to ensure compliance with their mission assurance requirements.

3.3 Risk Management Plan

The risk management strategy for the TINYSCOPE Project is to identify, analyze, plan, track, control, communicate and document critical areas and risk events, both technical and non-technical, and take necessary action to manage them

to prevent serious cost, schedule or performance impacts. The program investigators and sponsors acknowledge and accept the high risk associated with a technology demonstration spacecraft. Risk information will be included in all program reviews and the project will be continuously monitored for areas that may add to project risk and associated mitigation methods.

3.4 Acquisition Plan

Standard Naval Postgraduate School procurement guidelines will be followed at all times.

3.5 Systems Engineering Management Plan

The Systems Engineering Management Plan explicitly defines the major milestones and defines all deliverables for each milestone. The SEMP is tailored to the TINYSCOPE project. The primary function of the SEMP is to provide the basis for implementing the technical effort and communicating what will be done, by whom, when, where, cost drivers, and why it is being done. The SEMP identifies the roles and responsibility interfaces of the technical effort and how those interfaces will be managed. The SEMP specifies the deliverables for each phase and milestone of the project so that control gates (major reviews) may be passed without slippage of schedule or technical progress. The SEMP also defines the quality assurance plan and methodology for the project.

3.6 Software Management Plan

The Software Management Plan defines the format of communications between the various subsystems . Where any disparities arise between the Software Management Plan and individual subsystem documentation, the SMP take precedence.

3.7 Review Plan

The TINYSCOPE Project will conduct five major reviews prior to launch. Dates for the reviews will be maintained in the TINYSCOPE Master Schedule. The major reviews will consist of the following:

MRR – Mission Requirements Review

PDR – Preliminary Design Review

CDR – Critical Design Review

FRR – Flight Readiness Review

ORR – Operation Readiness Review

The purpose of the reviews are outlined in the Systems Engineering Management Plan (SEMP), but are generally used as control gates and evaluation of the progress of the flight hardware. Informal hardware development, science development and test readiness reviews will be conducted as necessary to evaluate interim development of the flight hardware.

3.8 Mission Operations Plan

The TINYSCOPE Mission Operations Plan applies to the prototype flight of the TINYSCOPE spacecraft and payload configuration. This plan provides the top level description of operations necessary to execute the mission. The plan will refer to specific documented procedures for detailed operations. This document outlines the sequence of events and operations to be conducted during the TINYSCOPE mission.

3.9 Environmental Management Plan

Environmental management of the spacecraft will be conducted in accordance with the Contamination Control Plan.

3.10 Logistics Plan

The TINYSCOPE logistics strategy is captured in several documents including the SEMP and Mission Operations Plan.

3.11 Data Management Plan

TINYSCOPE documentation and mission data will be maintained by the Nanosat Advanced Concepts Lab for the duration of the spacecraft mission and for a minimum period of 3 years following completion of deorbit. Access to data by parties external to the United States Government will be handled IAW applicable regulations and subject to the approval of the director of the Space Systems Academic Group. Documentation for this project includes, but is not limited to, management plans, specifications, reports, technical publications, schematics, drawings, production and inspection records, test plans, procedures and reports.

3.12 Security Plan

The TINYSCOPE Project will ensure security and technology protection by complying with applicable Naval Postgraduate School policies and procedures. The TINYSCOPE Project does not have plans to transfer or ship any products outside of the U.S. All Mission Operations and

handling of hardware will occur at designated NASA or U.S.
Air Force facilities. Wherever possible the TINYSCOPE
project will utilize hardware that is not regulated under
export control laws. However, as necessary the TINYSCOPE
Project will adhere to the the Arms Export Control Act
(Title 22, U.S.C., Sec 2751, et seq.) and the Export
Administration Act of 1979, as amended (Title 50, U.S.C.,
App. 2401 et seq.)

APPENDIX B -CERTIFICATION AND REQUIREMENTS DOCUMENT

This document is a part of the TINYSCOPE Project Documentation, controlled by the TINYSCOPE Project Manager under the direction of the Nanosat Advanced Concepts Laboratory at the Naval Postgraduate School, Monterey, CA.

APPROVAL:

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Record Of Revisions

REV	DATE	AFFECTED PAGES	DESCRIPTION OF CHANGE	AUTHOR
A	9/15/10	All	Baseline	Chris Turner
B				
C				
D				

1 INTRODUCTION

1.1 Purpose

This document delineates the design, construction, performance, and verification requirements for the TINYSCOPE Project. This document additionally defines all tests, analyses, inspections and certification methods required for all applicable flight hardware. Acceptance tests will be conducted to ensure that critical performance parameters are likely to be achieved. The TINYSCOPE project is primarily used as a vehicle for student research and hands on experience with design, construction and integration of satellite hardware. Due to the project's size, scope, cost and schedule, the risk constraints for the project are somewhat relaxed when compared to traditional space flight. As such qualification testing is required only for verification of safety compliance and interface compatibility with the launch vehicle adapter. This document will serve as both a planning guide and a checklist for verifying that all conditions are met to include design certification, acceptance testing and qualification testing.

1.2 Scope

This document provides the baseline requirements for the TINYSCOPE spacecraft. The document is published to provide necessary guidance to engineering for development of system design solutions. No specific design solution is specified by this document.

1.3 Definitions

The following definitions differentiate between requirements and other statements.

Shall: This is the only verb used for the binding requirements.

Should/May: These verbs are used for stating non-mandatory goals.

Will: This verb is used for stating facts or declaration of purpose.

1.4 Responsibility and Change Authority

The responsibility for the development of this document lies with the TINYSCOPE Project Team at the Naval

Postgraduate School. Derived requirements will be added to this document following a quarterly review process by the Student Program Manager and Systems Engineer until the Critical Design Review. Following CDR, the change authority will be the Student Program Manager with concurrence of both Principal Investigators.

2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 Reference Documents

The following documents are reference documents utilized in the development of this specification. These documents do not form a part of this specification, and are not controlled by their reference herein.

2.2 Order of Precedence

All specifications, standards, exhibits, drawings or other documents that are invoked as "applicable" in this requirements document are incorporated as cited. All documents that are referred to within an applicable document are considered to be for guidance and information only, with the exception of Interface Control Documents that shall have their applicable documents considered to be incorporated as cited.

2.3 Application and Traceability

These requirements will drive the derivation of functional, physical, and performance specifications for the TINYSCOPE project. The verification of these requirements shall certify this hardware for flight. These requirements shall be traceable to the functions and physical configuration items that meet the requirements.

3 KEY PERFORMANCE PARAMETERS

The TINYSCOPE Project has a number of Key Performance Parameters (KPPs) that are considered critical or essential to the demonstration of an effective capability. Each KPP has a threshold, representing the required value, and an objective, representing the desired value.

3.1 Mission Duration (KPP 1)

The satellite shall be operational for a period of six months following commissioning (threshold) and should be designed for operations of one year (objective). Operational is defined as having the capability to receive

commands, point to and collect images of given targets, and transmit collected data to the ground station.

3.2 Earth Imaging Resolution (KPP 2)

The satellite shall provide panchromatic images of the earth in the visible spectrum with an effective ground sampling distance of 5.0m (threshold) at nadir and should be designed to achieve a ground sampling distance of 3.1m (objective).

3.3 Telescope Field of View (KPP 3)

The satellite shall have a swath area of 25 square kilometers (threshold) at nadir and should be designed to achieve a swath area of 50 square kilometers at nadir (objective).

3.4 Image Collection Capacity (KPP 4)

The satellite shall be capable of collecting and transmitting to an accessible ground station, two diametrically opposed off-nadir images (threshold) in a ten degree along track band. The satellite should be capable of collecting and transmitting four diametrically opposed off-nadir images (objective) in a ten degree along track band.

3.5 Geo-location Accuracy (KPP 5)

The satellite shall have a circular ground targeting error of less than 200m (threshold) and should be designed to reduce error to less than 100m (objective).

4 MISSION HARDWARE REQUIREMENTS

4.1 Description

4.1.1 Payload
The TINYSCOPE payload will be composed of the telescope, camera module, all associated control electronics, all associated mounting, focusing, and alignment hardware, and required software to meet payload performance requirements.

4.1.2 Spacecraft
The TINYSCOPE spacecraft provides power to the focal plane array, attitude and thermal control, command and data handling and communications.

4.1.3 Communications Ground Station
The TINYSCOPE ground station will provide an intermittent link between the satellite and the flight operations

element. The ground station consists of a steerable
antenna, a telemetry tracking receiver, high and low
frequency synthesizers and computer hardware with orbit
propagation software.

4.1.4 Mission Operations Center

The Mission Operations Center consists of three operational
elements: flight operations, activity planning and data
management. The flight operations element communicates
with and controls the satellite through the ground station.
Activity planning and data management interact with the end
user of the TINYSCOPE product.   Figure 11 shows how each
element interacts with others.

4.2 TINYSCOPE Satellite Assembly

This   section   of   this   document   describes   all
functional,   performance,   physical,   and   technical
attributes, characteristics, requirements and constraints
that are applicable to the spacecraft.

4.2.1 Functional Requirements

TINYSCOPE Payload Subsystem

TR-1 The payload shall allow on-board imagery
processing and compression operations to be
selectively disabled.

TR-2 The payload shall meet or exceed imagery
requirements at all points in orbit and in
orientations up to 30 degrees off-nadir to either
side of the orbital plane.

TR-3 The payload shall remain fully functional at all
points in orbit and in orientations up to 30 degrees
off-nadir to either side of the orbital plane.

TR-4 The payload shall have instrument OFF, SAFE and
OPERATIONAL modes.

TR-5 The payload shall continue to collect and
transmit telemetry data to the spacecraft when in
SAFE mode.

TR-6 The payload shall be commanded by the
spacecraft.

TR-7 The payload shall autonomously enter SAFE mode
in the event of direct solar illumination.

TR-8 The payload shall be in OFF mode during launch.

TINYSCOPE Bus Subsystem

TR-9 The spacecraft shall autonomously activate following deployment from the launch vehicle.

TR-10 The spacecraft shall autonomously maneuver to a stable attitude following deployment from the launch vehicle.

TR-11 The spacecraft shall autonomously acquire the sun after deployment from the launch vehicle.

TR-12 The spacecraft shall autonomously enter an attitude that maximizes sun exposure after attitude stabilization.

TR-13 The spacecraft shall be capable of being commanded into any operational mode from the ground.

TR-14 The spacecraft shall autonomously transition to SAFE mode upon detection of any fault that threatens the health and safety of the spacecraft.

TR-15 The spacecraft shall transition out of SAFE mode only after command from the ground.

TR-16 Spacecraft autonomous functions shall be performed using on-board software.

TR-17 The spacecraft shall be capable of initiating a stored response to pre-defined telemetry conditions.

TR-18 The spacecraft shall record all autonomous operations to the telemetry log.

TR-19 The spacecraft shall report detection of out of limit conditions for monitored systems in the telemetry log.

TR-20 The spacecraft shall command the payload to SAFE mode when the sun is predicted to enter the field of view.

Electrical Power Subsystem (EPS)

TR-21 The EPS shall provide a single point ground within the power subsystem.

TR-22 The EPS shall provide power generation, power control, energy storage and distribution to the Spacecraft.

TR-23 The EPS shall provide conditioned electrical power for all Spacecraft operational modes during eclipse conditions.

TR-24 The EPS shall provide battery management and load shedding control.

TR-25 The EPS shall distribute direct current power to the loads at either 3.3 or 5 Volts.

TR-26 The spacecraft shall return to a full state of charge condition in the battery at least once in five orbits.

TR-27 The spacecraft shall be capable of autonomously assuming a maximum sun exposure orientation upon detection of a low battery charge state.

TR-28 The spacecraft shall be in an orientation that maximizes exposure of the solar array to the sun while in SAFE mode.

TR-29 The EPS shall provide short circuit protection or current limitation for each switchable power circuit.

TR-30 The EPS shall provide protection from over voltage and under voltage conditions.

TR-31 The spacecraft shall be capable of being powered from an external source while on the ground with or without batteries installed.

TR-32 The EPS shall at a minimum monitor and report in telemetry logs the switch positions, current, and voltage levels for each circuit at the power distribution point.

TR-33 The spacecraft battery capacity shall be 1.25 times the nominal charge / discharge profile at the end of the spacecraft design life.

TR-34 The EPS shall be capable of electrically bypassing failed battery cells.

Attitude Control and Determination Subsystem

TR-35 The Spacecraft shall remain thermally stable, under stable attitude control, and operationally functional within its design requirements up to 30 degrees off-nadir on either side of the orbit plane.

TR-36 The Spacecraft shall use the UTC time as the spacecraft time reference.

TR-37 The Spacecraft shall be capable of receiving a ground base Spacecraft reference time and time correction coefficients.

TR-38 The Spacecraft shall generate an on-board ephemeris based on the Global Positioning System (GPS) and on-board star tracker.

TR-39 The Spacecraft shall include the GPS carrier phase and pseudo range values in the spacecraft ancillary data stream.

TR-40 The Spacecraft shall be capable of receiving a ground based ephemeris update.

TR-41 The Spacecraft shall report the orbital position and velocity once per second in the spacecraft telemetry log.

Communications Subsystem

TR-42 The Communications Subsystem shall provide two-way RF communications for uplink of command and control data and downlink of payload data and satellite health and status data.

TR-43 The Communications Subsystem shall comply with National Telecommunications and Information Administration (NTIA) Spectrum Standards.

TR-44 The Communications Subsystem shall comply with International Telecommunication Union (ITU) spectrum utilization and sharing requirements.

TR-45 The Communications Subsystem shall be capable of reception of ground commands while in any operational mode.

TR-46 The Communications Subsystem shall be capable of transmissions in any operational mode.

TR-47 The Communications Subsystem shall be capable of transmissions in any orientation.

TR-48 The primary communications system shall be powered at all times except when the satellite is in EMERGENCY Mode.

TR-49 The primary communications system shall be capable of being enabled and disabled via ground command.

TR-50 The primary communications system shall be S-band.

TR-51 The command uplink shall be encrypted.

TR-52 The beacon system shall provide broadcasts in compliance with FCC Amateur Radio Regulations (Part 97).

TR-53 The beacon system shall be powered from activation through the life of the mission.

TR-54 The beacon system shall be capable of being enabled and disabled via ground command.

TR-55 The beacon system shall be capable of receiving commands in all spacecraft operational modes.

TR-56 The beacon system shall be automatically disabled after 21 days in the event that no satellite commands are received.

TR-57 The beacon system shall be designed such that its broadcasts can be reliably received with a typical OSCAR-class amateur radio communication station.

TR-58 The beacon system shall utilize AX.25 encoding protocol using 1200 baud, 1 start bit, 8 data bits, and 1 stop bit format.

TR-59 The beacon system shall broadcast data messages of up to 64 characters of telemetry and messages from the bus for transmission within the beacon broadcasts, which shall contain the "TINYSCOPE" character string in its packet.

Command and Data Handling Subsystem

TR-60 The Spacecraft shall be capable of monitoring the health and safety of the spacecraft and payload.

TR-61 The Spacecraft shall report in spacecraft telemetry log the health and safety of the spacecraft and payload.

TR-62 The Spacecraft onboard processor shall be capable of being reset via a ground command.

TR-63 The Spacecraft shall convert analog sensor data to digital format.

TR-64 The Spacecraft shall transmit real-time telemetry data to the ground when in contact with a ground station.

TR-65 The Spacecraft shall record all telemetry data.

TR-66 The Spacecraft shall be capable of concurrent transmission and storage of real-time telemetry.

TR-67 The Spacecraft shall report command acceptance or rejection in telemetry log upon receipt.

TR-68 The Spacecraft shall report command execution in telemetry log.

TR-69 The Spacecraft shall be capable of playing back stored telemetry data while in any mode.

TR-70 The Spacecraft shall be capable of decrypting command and data uploads using civil decryption coding.

TR-71 The Spacecraft shall be capable of source authentication of all received commands.

TR-72 The Spacecraft shall execute only commands that are source authenticated.

TR-73 The Spacecraft shall have a command authentication bypass.

TR-74 The Spacecraft command authentication bypass shall be accomplished by means of a fixed length timer.

TR-75 The Spacecraft shall autonomously reset the authentication bypass timer upon receipt of a successfully authenticated command.

TR-76 The Spacecraft shall reject invalid commands.

TR-77 The Spacecraft shall identify rejected commands in telemetry log(s).

TR-78 The Spacecraft shall validate, process, and execute flight software update commands, ephemeris table data, and star database loads.

TR-79 The Spacecraft shall be capable of receiving command loads across multiple contacts.

TR-80 The Spacecraft shall be capable of receiving flight software updates across multiple contacts.

TR-81 The Spacecraft shall use unique commands to change state and condition.

TR-82 The Spacecraft shall record all mission data.

TR-83 The Spacecraft shall be capable of resending stored mission data multiple times.

TR-84 The Spacecraft shall retain all stored data when transitioning into and out of any operational mode.

TR-85 The Spacecraft shall acquire ephemeris and ancillary data from the spacecraft that is necessary to meet instrument imaging requirements.

TR-86 The Spacecraft shall use a file based data management scheme for stored data.

TR-87 The Spacecraft shall provide a listing or directory of its file system including file attributes on command.

TR-88 The Spacecraft shall maintain mass storage file attributes that include at a minimum:

- A file name
- A unique time stamp
- The file length

- Flags that provide data protection status (over-write or not)
- Flag that indicates whether the file has been transmitted

TR-89 The Spacecraft shall uniquely identify each data file in mass storage using a root name associated with the ground location of the data content.

TR-90 The Spacecraft shall designate any single or set of mission data files as protected on command.

TR-91 The Spacecraft shall autonomously mark mission data files in mass storage as non-protected after acknowledgement of receipt by the ground station.

TR-92 The Spacecraft shall designate any single or set of mission data files as non-protected on command.

TR-93 The Spacecraft shall only overwrite non-protected mission data.

TR-94 The Spacecraft shall overwrite mission data starting from oldest to youngest.

TR-95 The Spacecraft shall be capable of repeat playbacks of stored data.

TR-96 The Spacecraft shall autonomously determine which mass storage files will be down- linked at the next ground contact opportunity.

TR-97 The Spacecraft shall downlink mass storage files in a non-standard order upon command from the ground.

TR-98 The Spacecraft shall retransmit individual files on command.

TR-99 The Spacecraft shall be capable of diagnosing mass storage problems.

TR-100 The Spacecraft shall have autonomous internal fault detection and responses for each subsystem.

TR-101 The Spacecraft shall record in telemetry log that faults responses have been completed.

Thermal Control

TR-102 The Spacecraft shall be thermally safe for continuous operations in all operational modes.

TR-103 The Spacecraft shall have a thermal control system that monitors and reports in the telemetry log the temperatures of subsystems on the Spacecraft.

Structural and Mechanical

TR-104 The Spacecraft structure shall provide a structural mounting interface with a nadir field-of-view clear of obstructions for the payload.

TR-105 The Spacecraft structure shall include a structural mounting interface that is isolated from mechanical and thermal disturbances from the Spacecraft

TR-106 The Spacecraft shall be designed to permit full range deployment of mechanisms after integration with the Spacecraft during ground processing.

Flight Software

TR-107 The Spacecraft flight software shall be reprogrammable on orbit.

TR-108 The Spacecraft shall monitor software tasks to detect for infinite loops or stalled processes.

TR-109 The Spacecraft flight software shall detect and correct single bit memory errors.

TR-110 The Spacecraft stored commands shall be unaffected by a flight software upload.

TR-111 The Spacecraft flight software shall store the version identifier of reprogrammable software onboard.

TR-112 The Spacecraft shall preserve contents of the telemetry log after rebooting or power cycling.

TR-113 The Spacecraft shall initialize flight software and begin operations without the need of a ground based command.

TR-114 The Spacecraft processor shall execute a restart of its software in response to a ground command.

TR-115 The Spacecraft flight software shall provide a capability to store and execute absolute-time command sequences.

TR-116 The Spacecraft flight software shall provide a capability to store and execute relative-time command sequences.

TR-117 The Spacecraft flight software shall execute real-time commands before executing stored commands.

TR-118 The Spacecraft flight software shall provide the capability to store multiple time-tagged command sequences.

TR-119 The Spacecraft flight software stored command sequences shall be modifiable by ground command.

TR-120 The Spacecraft flight software command sequences shall be enabled, disabled or canceled by ground command.

TR-121 The Spacecraft flight software shall be capable of placing the contents of the stored command buffer into the telemetry log.

TR-122 The Spacecraft flight software shall uniquely identify stored command sequences.

TR-123 The Spacecraft flight software shall use the unique command sequence identifier to report the status of each actively executing command sequence in telemetry.

4.1.2 Performance Requirements
4.2.1.1 TINYSCOPE Payload Subsystem

TR-124 The payload shall have a minimum field of view that provides a 25 square kilometer swath when nadir pointing.

TR-125 Data compression algorithms applied to image data shall be lossless.

TR-126 Non-uniformity correction algorithms shall be fully reversible and coefficients shall be transmitted with each image file.

TR-127 The payload shall provide a pixel-to-pixel increment, in both the along track and cross track directions, equivalent to a Ground Sampling Distance (GSD) less than or equal to 4 meters for a panchromatic band.

TR-128 Payload data shall be quantized to a minimum of 8 bits.

TR-129 The payload structure shall be of sufficient strength and stiffness to maintain structural integrity during ground testing and transportation and launch.

TR-130 The payload structure shall provide a mounting interface to the spacecraft bus.

TR-131 The payload structure shall include a mechanical alignment device to co-align the optical path to the spacecraft bus structure and inertial reference frame.

TR-132 The payload mechanical alignment device shall be internally stable through the full range of design temperatures.

TR-133 The payload shall be thermally stable while in operational modes.

TR-134 The payload shall be designed to operate from a 5V direct current power subsystem.

TR-135 The payload shall have an average power consumption that does not exceed 8 Watts.

TR-136 The payload shall have a peak power consumption that does not exceed 10 Watts.

TR-137 The payload software shall be reprogrammable on orbit.

TR-138 The payload processor shall be capable of being reset on orbit.

TR-139 The payload processor shall continuously monitor its health and safety.

TR-140 The payload shall time tag image data with accuracy of 1 millisecond relative to the spacecraft time reference.

TR-141 The payload software shall provide sufficient telemetry to ensure proper control and monitoring of health and safety and to identify anomalous conditions.

TR-142 The payload shall be designed to operate and meet all design requirements for six months following commissioning on orbit.

TR-143 The payload shall be capable of being placed in a state of storage without requiring maintenance for a period of six months.

4.2.1.2 TINYSCOPE Bus Subsystem

TR-144 The spacecraft shall be capable of operating safely without any ground intervention for a period of 72 hours.

Electrical Power Subsystem

TR-145 The spacecraft shall provide continuous and peak power with a 20% margin for all phases of mission operation.

Attitude Control and Determination Subsystem

TR-146 The Spacecraft shall perform maneuvers to any inertial attitude meeting pointing requirements and stabilize within 90 seconds.

TR-147 The spacecraft shall have absolute pointing accuracy of less than or equal to 0.1 degrees.

TR-148 The Spacecraft shall compute orbital position accurate to 30 m radial, 30 m in-track, and 30 m cross-track.

TR-149 The Spacecraft shall provide orbital velocity accurate to 0.30 m/sec radial, 0.30 m/sec in-track, and 0.30 m/sec cross track.

TR-150 The Spacecraft shall be capable of propagating the on-board state for at least 24 hours.

TR-151 The spacecraft shall support imaging operations for up to 24-hours from an onboard propagated ephemeris.

Communications Subsystem

TR-152 Radio frequency link margins shall be at least +3dB in all operational modes.

TR-153 The spacecraft shall transmit a minimum of 90% of real-time and recorded telemetry to the ground segment.

TR-154 The primary communications system shall have a bit error rate (BER) at operational data rates of less than or equal to 1E-6 after demodulation and error correction.

TR-155 The primary command uplink shall be at 16 Kbps.

TR-156 The primary downlink shall at a minimum be 1.2 Mbps.

TR-157 The backup command uplink shall be at a minimum 250 bps to the beacon system.

TR-158 The backup downlink through the beacon system shall be at a minimum 200 bps.

TR-159 The beacon system shall have minimum broadcast repetition rates on the order of 5-60 seconds.

TR-160 The beacon system shall have a bit error rate (BER) at operational data rates of less than or equal to 1E-5 after demodulation and error correction.

Command and Data Handling Subsystem

TR-161 The Spacecraft shall be capable of storing at least 72 hours of Spacecraft telemetry data at the maximum onboard telemetry rate.

TR-162 The Spacecraft shall be capable of storing at least 72 uncompressed images and associated ephemeris and ancillary data.

TR-163 The Spacecraft shall time tag ephemeris and ancillary data to the spacecraft time reference with an accuracy of 1 millisecond.

TR-164 The Spacecraft shall time-tag telemetry data to the spacecraft time reference with an accuracy of 1 millisecond.

Structural and Mechanical

TR-165 The Spacecraft structure shall be sufficiently stiff to meet the axial and lateral frequency requirements as defined in GSFC-STD-7000.

TR-166 The Spacecraft structure shall be of sufficient strength and stiffness to maintain structural integrity and withstand all launch and launch vehicle separation environments as defined in GSFC-STD-7000.

TR-167 The Spacecraft structure shall be of sufficient strength and stiffness to maintain structural integrity and withstand all ground testing, handling, transportation, and mission on-orbit environments as defined in GSFC-STD-7000.

Flight Software

TR-168 The Spacecraft flight software stored command capability shall store up to 72 hours of spacecraft command sequences.

TR-169 The Spacecraft flight software shall be capable of executing commands with an accuracy of 100 milliseconds or less.

4.1.2 Physical Characteristics

TR-170 The TINYSCOPE system mass shall consist of the TINYSCOPE satellite bus and the payload subsystem with a launch mass of 14 kg or less.

TR-171 TINYSCOPE shall conform to all applicable standards for the Nanosatellite Launch Adapter System.

4.1.3 Environmental Requirements

TR-172 All subsystems shall be qualified at acceptance levels for Thermal Cycle, Thermal Vacuum

Cycle, Vibration, and Shock Testing as defined in GSFC-STD-7000.

TR-173 The satellite bus and payload electronics shall be capable of correcting for single event memory corruption caused by radiation.

TR-174 The TINYSCOPE spacecraft and payload shall be capable of operation in low Earth orbit (LEO) without unrecoverable failure due to radiation effects.

4.3 Communications Ground Station (GS)

4.3.1 Functional Performance

TR-175 The GS shall provide the capability to measure beacon signal strength.

TR-176 The GS shall provide the capability to autonomously steer the antenna in azimuth and elevation to track the beacon signal.

TR-177 The GS shall provide the capability to manually steer the antenna in azimuth and elevation to track the beacon signal.

TR-178 The GS shall have the capability to receive transmissions from the satellite primary communications system.

TR-179 The GS shall have the capability to encode and decode beacon and primary signals.

TR-180 The GS shall have the capability to receive commands and scripts from the MOC.

TR-181 The GS shall have the capability to transfer data to the MOC.

TR-182 The GS shall have the ability to be controlled from the MOC.

TR-183 The GS shall have the capability to encrypt and decrypt communications.

TR-184 The GS shall have the capability to propagate satellite orbits.

TR-185 The GS antenna shall have the capability to scan.

TR-186 The GS shall have the capability to transmit and receive simultaneously.

4.4 Mission Operations Center (MOC)

4.4.1 General

TR-187 The MOC shall use Universal Time Coordinated (UTC) time as the time base for all operations activities.

TR-188 The MOC shall receive all data for the life of the mission.

TR-189 The MOC shall support end of life decommissioning activities.

TR-190 The MOC shall support a single 8-hour by 5-day shift (M-F) approach and operate autonomously whenever not staffed.

TR-191 All functional applications in the MOC shall have the ability to run unattended while performing all routine and periodic operations for 72 hours.

TR-192 The MOC shall autonomously monitor the event log and notify appropriate on-call personnel when the MOC is not staffed.

TR-193 The MOC shall generate commands for transmission to the spacecraft.

TR-194 The MOC shall accept telemetry and mission data from the spacecraft.

TR-195 The MOC shall send spacecraft commands to the ground station for S-band uplink.

TR-196 The MOC shall receive real-time telemetry from the ground station.

TR-197 The MOC shall receive stored telemetry logs from the ground station.

4.4.2 Activity Planning Element (APE)

TR-198 The APE shall provide the capability to plan and schedule all spacecraft collection and maintenance activities for the life of the mission.

TR-199 The APE shall produce time-ordered activity plans listing all planned activities for the spacecraft planning window.

TR-200 The APE shall incorporate all resource down times or reserved times into schedule generation events.

TR-201 The APE shall convert collection and maintenance requests into spacecraft activities.

TR-202 The APE shall provide the capability to create and modify activity priorities, constraints, and rules.

TR-203 The APE shall automatically check for activity constraint and rule violations during schedule generation.

TR-204 The APE shall automatically check for resource constraint and rule violations during schedule generation.

TR-205 The APE shall provide the capability to automatically schedule all spacecraft and ground station activities within operational resource constraints.

TR-206 The APE shall provide the capability to produce a Coordinated Universal Time (UTC) time-based activity schedule in terms of specific start/stop times.

TR-207 The APE shall provide the capability to generate a conflict-free activity schedule spanning 72-hours of activity.

TR-208 The APE shall provide the capability to generate a graphical timeline of activity plans and schedules.

TR-209 The APE shall provide a display of planned, currently active and past observatory and ground activities.

TR-210 The APE shall produce and deliver activity schedules to the data management element.

TR-211 The APE shall be capable of archiving and recovering all planning and scheduling data for the life of the mission.

4.4.3 Flight Operations Element (FOE)

TR-212 The FOE shall interface with the ground communications network for the exchange of mission data and products among the ground system elements.

TR-213 The FOE shall provide an interface between the ground system elements and the space-ground communications links.

TR-214 The FOE shall provide an anomaly reporting and status tracking capability.

TR-215 The FOE shall ensure that no single point of failure exists for critical command and control functions.

TR-216 The FOE shall provide the capability to support training, testing, or system maintenance with no interruption to FOE functionality.

TR-217 The FOE shall provide the capability to log, track, and report system faults and failures.

TR-218 The FOE shall be capable of generating commands to perform the spacecraft functions.

TR-219 The FOE shall be capable of generating commands to support the retransmission of telemetry data.

TR-220 The FOE shall perform command encryption and authentication.

The FOE shall assign levels of command authority to ensure that only authorized personnel can perform designated command functions.

TR-221 Command authority shall be controlled by login attributes.

TR-222 The FOE shall provide the capability to allow authorized operators to transmit commands to the observatory.

TR-223 The FOE shall prevent simultaneous sending of commands by multiple operators.

TR-224 The FOE shall provide the capability to perform real time commanding to the observatory.

TR-225 The FOE shall perform verification of real-time commands to the observatory.

TR-226 The FOE shall provide the capability to generate, uplink, and verify discrete observatory commands.

TR-227 The FOE shall provide the capability to generate command sequences via a scripting language.

TR-228 The FOE shall provide the capability to uplink command scripts or software updates that are stored as named files.

TR-229 The FOE shall produce a load generation report for all loads, containing accounting information, description of load contents, any warning and/or error messages and a summary of creation results.

TR-230 The FOE shall be capable of performing automatic constraint and rule checking of discrete commands and command loads.

TR-231 The FOE shall require at least one additional operator confirmation prior to the transmission of commands or command sequences that have failed constraint check.

TR-232 The FOE shall be capable of notifying the operator that the commands sent to the spacecraft were correctly received.

TR-233 The FOE shall provide the capability to manually retransmit commands or command loads that were not accepted by the spacecraft.

TR-234 The FOE shall define spacecraft commands and their characteristics in a command database.

TR-235 The FOE shall have the capability to search and sort spacecraft commands defined in the command database.

TR-236 The FOE shall archive all command operations and command history for the life of the mission.

TR-237 The FOE shall provide the capability to time tag all spacecraft and ground system data with a UTC time.

TR-238 The FOE shall provide the capability to replay telemetry by ground receipt time or spacecraft time.

TR-239 The FOE shall provide the capability to display operator-selected telemetry data in real time.

TR-240 The FOE shall provide a capability to verify in real-time that telemetry parameters are within prescribed operating limits.

TR-241 The FOE shall define spacecraft telemetry and their characteristics in a telemetry database.

TR-242 The FOE shall have the capability to search and sort spacecraft telemetry defined in the telemetry database.

~~TR-243~~ The FOE shall be capable of ingesting and storing all telemetry data for trending and analysis.

TR-244 The FOE shall examine spacecraft data to determine if any unexpected deviations from the pre-planned timeline have occurred.

TR-245 The FOE shall produce an as-flown timeline that reflects the activities that were actually executed by the spacecraft.

TR-246 The FOE shall create pass summaries that describe the results of each spacecraft contact.

TR-247 The FOE shall perform evaluation of on-board derived ephemeris and attitude estimates available in the telemetry log.

TR-248 The FOE shall provide the capability to automatically detect when the spacecraft orbital parameters deviate from established limits.

TR-249 The FOE shall have the capability to perform real-time attitude estimation using raw sensor data in the telemetry data.

TR-250 The FOE shall provide the capability to generate the definitive ephemeris of the observatory at an accuracy of 30m in each axis.

TR-251 The FOE shall provide the capability to propagate the observatory orbit for 72 hours.

TR-252 The FOE shall produce data necessary to support Conjunction Assessment activities.

TR-253 The FOE shall receive data necessary to support Conjunction Assessment activities.

TR-254 The FOE shall propagate object ephemeris and compare results to predicted observatory ephemeris.

TR-255 The FOE shall have the capability to generate attitude estimates of accuracy meeting mission requirements from raw sensor data contained in telemetry logs.

TR-256 The FOE shall be capable of validating the on-board attitude estimates meet mission accuracy requirements.

TR-257 The FOE shall predict star tracker target fields and compare these predicts to star acquisition data available in telemetry logs on an as-needed basis.

TR-258 The FOE shall accept a star catalog from an external source and have the ability to maintain and uplink the star catalog.

TR-259 The FOE shall be capable of generating maneuver plans in support of all observatory attitude maintenance and collection activities.

TR-260 The FOE shall monitor on-board sensor calibrations and re-calibrate, as necessary to meet absolute attitude accuracy requirements.

TR-261 The FOE shall specify and generate attitude sensor calibration maneuver sequences to provide sufficient sensor data to derive sensor alignment &

calibration coefficients meeting mission attitude determination requirements.

TR-262 The FOE shall provide a capability to display the spacecraft orbit and ground tracks.

TR-263 The FOE shall be capable of ingesting externally-generated spacecraft ephemeris data.

TR-264 The FOE shall provide the capability to modify any re-programmable/writeable memory locations on the observatory.

TR-265 The FOE shall have the capability to command data in mass storage to be unprotected.

TR-266 The FOE shall provide a capability for operators to select data in mass storage for downlink.

TR-267 The FOE shall time tag all event messages with a UTC time.

TR-268 The FOE shall provide the capability to log all event messages for the life of the mission.

TR-269 The FOE shall provide the capability to display any event messages and logs.

TR-270 The FOE shall be capable of autonomously establishing a command and telemetry link with the ground station for every spacecraft contact.

4.4.4 Data Management Element (DME)

TR-271 The DME shall provide the capability to archive and retrieve engineering data products.

TR-272 The DME shall provide the capability to archive and retrieve telemetry data products.

TR-273 The DME shall provide the capability to archive and retrieve mission data products.

TR-274 The DME shall archive all mission data in raw and processed forms.

TR-275 The DME shall archive raw mission data in a separate archive from processed data.

TR-276 The DME shall provide the capability to authorize and limit access to archival databases.

TR-277 The DME shall provide the capability to distribute raw and processed mission data to users.

TR-278 The DME shall provide the capability to provide, at a minimum, the following basic services:

- Image georeferencing
- Orthorectification
- Correct radiometric distortion caused by instrumentation error

5 MISSION OPERATIONS REQUIREMENTS

TR-279 The spacecraft shall be powered off following integration and throughout launch operations.

TR-280 The TINYSCOPE satellite mission operations shall begin no later than 24 hours prior to launch.

TR-281 The TINYSCOPE System shall be capable of operations from the NPS Mission Operations Center.

TR-282 The spacecraft shall be designed to operate and meet all design requirements for six months following commissioning on orbit.

TR-283 The spacecraft shall be capable of being placed in a state of storage without requiring maintenance for a period of six months.

TR-284 The spacecraft shall be designed for an overall probability of success of 80% at the end of its design life.

TR-285 The spacecraft shall be compliant with NASA requirements for limiting orbital debris.

TR-286 The spacecraft shall be designed to operate in a sun-synchronous circular orbit at an altitude of 500 kilometers +- 120 kilometers.

TR-287 The spacecraft shall have three operational modes as follows:

- NORMAL Mode is the nominal operational mode for the spacecraft.

- SAFE Mode provides maximum sun exposure to the solar array and a spacecraft configuration that does not allow image collection. The payload and S-band radio are deactivated and the beacon system transmits continuous telemetry data through the omni-directional antenna.
- EMERGENCY Mode deactivates all subsystems with the exception of the beacon system. The beacon transmits a periodic distress signal along with telemetry data to preserve power. The EPS provides a direct path from the solar array to the battery for charging. The spacecraft is not capable of image collection, high rate communication, or attitude control in EMERGENCY Mode.

6 VERIFICATION REQUIREMENTS

6.1 Structural and Mechanical Verification Requirements

TR-288 Random vibration tests shall be conducted on the integrated spacecraft bus, payload system, and the final spacecraft assembly.

TR-289 Random vibration tests shall cover frequency ranges from 20 to 2000 Hz.

TR-290 Random vibration test items shall be subjected to random vibration along each axis for one minute each.

TR-291 Random vibration test qualification and acceptance test levels will be determined in accordance with GSFC-STD-7000.

TR-292 The mass properties of the integrated spacecraft shall be determined by measurement.

TR-293 The following mass properties shall be determined:

- Weight
- Center of gravity
- Moment of inertia
- Balance

TR-294 Subsystem qualification tests shall be performed for each mechanical operation.

TR-295 The integrated spacecraft shall be tested to demonstrate that each mechanical device is installed correctly and that there are no interference problems that will adversely affect the mission.

6.2 Electromagnetic Compatibility Verification Requirements

TR-296 Radiated emission tests shall be performed on spacecraft transmitters to identify electro-magnetic interference.

TR-297 The integrated spacecraft shall be tested for stray magnetic fields which may affect the on-board magnetometers.

6.3 Electrical Function Verification Requirements

TR-298 Electrical interface tests shall be performed on each component and subsystem prior to integration to verify that interface signals follow the correct signal path and are within acceptable limits.

TR-299 Electrical harnesses shall be tested to verify proper routing, impedance, isolation, and workmanship prior to integration.

TR-300 An aliveness test shall be performed prior to and following integration to verify that the component or subsystem is functioning.

TR-301 A comprehensive performance test (CPT) shall be conducted on each component and subsystem following environmental testing to demonstrate that components meet performance requirements within allowable tolerances.

TR-302 CPT shall be conducted at the hot and cold extremes of the thermal-vacuum test for both maximum and minimum input voltage.

6.4 Vacuum and Thermal Verification Requirements

TR-303 All components and subsystem assemblies shall be subjected to thermal-vacuum tests that demonstrate function at temperatures ten degrees higher and lower than expected flight temperatures.

TR-304 The integrated spacecraft shall be subjected to thermal-vacuum tests that demonstrate function at temperatures five degrees higher and lower than expected flight temperatures.

TR-305 Thermal-vacuum tests shall, at a minimum, subject hardware to four complete thermal cycles.

TR-306 Thermal-vacuum tests shall incorporate a period for out-gassing.

TR-307 CPT shall be performed at each hot and cold soak plateau of a thermal cycle.

6.5 Optical Calibration Requirements

TR-308 Spatial edge response shall be characterized based on measurements at the integrated payload level, before and after vibration testing and across the entire field of view in all bands.

TR-309 A stray light model shall be developed that includes the entire optical system including baffles, detectors and portions of the satellite bus that may reflect light into the sensor.

TR-310 The radiometric response of detectors shall be characterized across the expected operating temperature range of the payload.

TR-311 The payload shall be characterized to ensure that it will meet absolute radiometric accuracy, pixel-to-pixel uniformity and radiometric stability in expected orbital conditions.

TR-312 The signal to noise ratio of all detectors shall be characterized.

TR-313 The baseline 1/f noise parameters for all imaging detectors shall be characterized.

TR-314 The coherent noise of the integrated payload shall be characterized.

TR-315 The dark level coherent noise of the integrated payload shall be characterized.

TR-316 Dead, inoperable, and out-of-spec detectors shall be identified and recorded.

TR-317 Alignment of the telescope optical axis relative to the spacecraft shall be measured.

TR-318 Degradation of image quality due to internal spacecraft vibration shall be characterized.

TR-319 Degradation of image quality due to spacecraft motion shall be characterized.

TR-320 Alignment and focus changes to the optical path due to thermal expansion or contraction shall be characterized.

TR-321 Aberrational variations from design to production shall be measured and characterized.

TR-322 Variations in detector response shall be characterized through two out-gassing cycles.

APPENDIX C-CONTAMINATION CONTROL PLAN

This document is a part of the TINYSCOPE Project Documentation, controlled by the TINYSCOPE Project Manager under the direction of the Nanosat Advanced Concepts Laboratory at the Naval Postgraduate School, Monterey, CA.

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1 PURPOSE

This contamination control plan describes the requirements and procedures for the environmental management of the TINYSCOPE spacecraft. This plan is applicable during all phases of development to include fabrication, assembly, integration and test, and transportation and storage.

2 SPACECRAFT CONTAMINATION SOURCES

Contamination of a spacecraft may occur at anytime from the beginning of individual component fabrication through launch and into the spacecraft's service life. Table 1 below lists the spacecraft's development cycle and the contamination sources that must be guarded against in each phase.

Table 1. Contamination Sources for Spacecraft. Taken from (Contamination Control Plan for Midshipman Space Technology Applications Research MidSTAR)-1 Spacecraft, 22 June 2004.)

Development Phase	Molecular	Particulate
Fabrication	materials out-gassing, machining oils, fingerprints, air fallout	shedding, flaking, metal chips, filings, air fallout, personnel
Assembly & Integration	air fallout, out-gassing, personnel, cleaning, solvents, soldering, lubricants, bagging material	air fallout, personnel, soldering, drilling, bagging material, shedding, flaking
Test	air fallout, out-gassing, personnel, test facilities, purges	air fallout, personnel, test facilities, purges, shedding, flaking, redistribution
Storage	bagging material, out-gassing, purges, containers	bagging material, purges, containers, shedding, flaking
Transport	bagging material, out-gassing, purges, containers	bagging material, purges, containers, vibration, shedding, flaking
Launch Site	bagging material, air fallout, out-gassing, personnel, purges	bagging material, air fallout, personnel, shedding, flaking, checkout activities, other payload activities

Launch/Ascent	out-gassing, venting, engines, companion payloads separation maneuvers	vibration and/or redistribution, venting, shedding, flaking
On-Orbit	out-gassing, UV interactions, atomic oxygen, propulsion systems	spacecraft cloud, micrometeoroid & debris impingement, material erosion, redistribution, shedding, flaking, operational events

3 CONTAMINATION CONTROL REQUIREMENTS

In general the assembly and integration of the spacecraft will take place in a Class 6 (ISO) clean room. When testing or transportation requires the spacecraft to leave the clean environment, it should be bagged. Hardware that is not being actively used or worked on should be covered even when in the clean room environment. Hardware should remain surface clean in visible light at all times.

3.1 FABRICATION, ASSEMBLY, & INTEGRATION

Components of the spacecraft may be fabricated in uncontrolled environments. This does not preclude the need for contamination controls. These parts should still be surface clean at all times and should be bagged whenever possible. Prior to entry into the clean environment, each component will be cleaned thoroughly with a compatible solvent and will be inspected.

During the assembly phase, all parts will be stored and assembled in the clean room. All test and support equipment will be cleaned prior to entry to the clean room and will be kept to the same standard of cleanliness as the spacecraft components while in the room. During operations that require soldering or the application of lubricants, contaminants should be removed immediately after the operation using an appropriate solvent. Areas that will become inaccessible due to assembly should be thoroughly cleaned and inspected prior to the assembly.

3.3 TESTING & TRANSPORTATION

Generally, contamination requirements during testing and transportation are the same as in previous phases. However, there may be cases where coverings must be removed to perform a test. In this case, personnel must don clean room clothing and gloves prior to handling the spacecraft. During periods of inactivity, the spacecraft will be draped. Out-gassing tests and vacuum bakeouts must be

followed immediately by a thorough cleaning of the
spacecraft's surfaces. After cleaning is complete, the
spacecraft will be visually inspected. It will then be
double bagged for transportation between facilities. The
Spacecraft will be transported in a shipping container that
has been be pre-cleaned to a visibly clean level.
Temperature and humidity will not be monitored in the
shipping container.

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